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Storm Water Management Model Study Volume II

Research Report No. 48



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**Research Program for the Abatement of Municipal Pollution
under Provisions of the Canada-Ontario Agreement
on Great Lakes Water Quality**

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RESEARCH REPORTS

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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STORM WATER MANAGEMENT MODEL STUDY

VOLUME II

Technical Background

by

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RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
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AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

This volume, Volume II of a three-volume report, contains supplementary technical material used in preparing the final report, Volume I.

Comparative analyses of six storm water routing models and four water quality models are described. Literature surveys are included for material dealing with urban runoff quality and snowmelt quantity and quality. Sources of data required for storm water modelling have been assessed, and study areas in Canada and the U.S. are described. A summary of the treatment processes available in the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is given, and current literature and modifications to the treatment model are described.

RÉSUMÉ

Le présent volume, le deuxième d'une série de trois, renferme les données techniques supplémentaires dont se sont servis les auteurs du rapport définitif que contient le premier volume.

On y fait l'analyse comparative de six modèles estimatifs de l'acheminement des eaux pluviales et de quatre modèles estimatifs de la qualité de l'eau. Les parties traitant des aspects qualitatifs des eaux de ruissellement urbain et des aspects tant quantitatifs que qualitatifs des eaux de fonte comportent une bibliographie. Les auteurs ont évalué les sources des données ayant servi à établir les modèles d'acheminement des eaux pluviales; en outre, ils décrivent les régions du Canada et des Etats-Unis sur lesquelles a porté l'étude. Le lecteur trouvera, de plus, un exposé sommaire des procédés de traitement que comporte le modèle de gestion des eaux pluviales (SWMM)* de l'Environmental Protection Agency ainsi qu'une liste de publications récentes et des notes utiles sur les modifications se rapportant à ce modèle.

*Storm Water Management Model

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1. COMPARATIVE ANALYSIS OF ROUTING MODELS

With the advent of high-speed computers and recent developments in numerical techniques, improved methods have been proposed for solving sewer flow problems. These new methods involve the application of more sophisticated hydraulic equations. The two basic equations representing the gradually varied free-surface unsteady flow are the momentum equation:

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial h}{\partial x} - g (S_o - S_f) = \frac{V \cdot q}{A}$$

and the corresponding equation of continuity:

$$\frac{\partial h}{\partial t} + \frac{A}{B} \frac{\partial V}{\partial x} + V \frac{\partial h}{\partial x} = \frac{q}{B}$$

where: V = velocity

t = time

x = longitudinal coordinate along channel bottom
direction

g = gravitational acceleration

h = depth of flow

S_o = channel bottom slope

S_f = friction slope

q = the distributed lateral inflow (or outflow)
as discharge per unit length of the conduit

A = area of channel cross section

B = water surface width.

These are quasi-linear hyperbolic first-order partial differential equations derived from the well-known St. Venant equation by adding the right hand side to each, which represents the effect of the lateral flow. These two equations can be solved numerically by using the method of characteristics. Although this method gives the most accurate of all practical methods of flood routing in channels and conduits, it requires a considerable amount of computation, and difficulties are also encountered in defining the boundary conditions. Hence, various simplifications have been proposed to give simple approximate solutions.

One approach, which is known as hydrologic routing, is to use only the continuity equation. The hydrologic routing techniques, including the various coefficient routing methods such as the Muskingum technique and the reservoir routing technique, are used in some sewer flow models. Another approach is to solve the continuity equation together with various simplifications of the momentum equation. Among these are the kinematic wave approximation and the diffusion wave approximation. All the aforementioned flow routing techniques are applicable to a single sewer. When these techniques are applied to a network, the sewers or channels are simply treated individually in sequence with the flow cascading downstream from one channel to another. However, in a sewer network, considerations must be given to such mutual dynamic effects as backwater and energy losses among sewers and junctions.

Some of the sewer flow models are discussed in this section. The comparison is based on the following criteria:

- a) the routing technique;
- b) the degree of approximation used; and,
- c) the level of consideration of the backwater and energy losses in the junctions.

It should be noted that only the more sophisticated routing models which are necessary for large systems are included. Simplified models such as those considered by the RRL and the UCUR will be discussed in Section 3 and they are valid only for small areas with small sewer reaches.

(i) High-speed model developed by the Colorado State University, MWIS:

The Muskingum technique is used, combined with an approximate form of the St. Venant momentum equation (inertia terms are neglected). With the routing coefficients changing each time step, some restrictions on the size of the routing time interval have to be used in order to assure mass conservation.

Another restriction applies to the slope of the pipe,

which has to be significantly greater than zero; otherwise, Muskingum's technique is not applicable. The model does not take into account either backwater effects or junction storage. Junctions are considered as point nodes and the hydrograph is routed through each single sewer, regardless of the effect of the downstream parts of the system.

(ii) The SWM Model, U.S. EPA [1]:

The transport model of the U.S. Environmental Protection Agency (EPA) uses a simpler form of the St. Venant equations. The continuity equation is solved with the quasi-steady dynamic-wave approximation, which is the momentum equation with the rate of change of velocity term neglected. While an implicit scheme is used to solve the continuity equation, an explicit scheme has been adopted for the momentum equation. With the latter acting as an auxiliary equation, a Newton-Raphson technique is used to solve the nonlinear continuity equation. The friction slope is evaluated from Manning's formula, and the lateral flow is not simulated.

Like the MWIS model, no consideration is given to the backwater effects on the junction storage. However, lift stations, flow dividers and reservoir routing techniques are modelled.

The model has been compared with the method of characteristics for a single line, but there is no indication about its accuracy when the backwater effect has a considerable role in the flow characteristics of a big system.

(iii) Improved SWMM developed by Water Resources Engineers Inc. Systems, WRE [2]:

The motion and continuity equations are used as follows:

$$\frac{\partial Q}{\partial t} = -g A S_f + 2V \frac{\partial A}{\partial t} + V^2 \frac{\partial A}{\partial x} - gA \frac{\partial h}{\partial x}$$

$$\text{and } \frac{\partial h}{\partial t} = \frac{\sum Q_t}{A_{st}}$$

where: $\sum Q_t$ = total inflow and outflow to the junctions at time t

A_{st} = water surface area in the junction at time t .

The motion equation is applied to each link and the continuity equation to each node. Since an explicit approach, by the use of the modified Euler method, is used there is a restriction on the size of the routing time step. If the time step is chosen higher than a certain limit, the solution becomes unstable. Although this limit has been determined by:

$$\Delta t \leq \frac{L}{2 V_{\max}}$$

where: Δt = time step

L = conduit length,

it was found that a more appropriate stability relationship is

$$\Delta t \leq \frac{C A h_{\max}}{\sum Q}$$

where C is a constant determined experimentally as 0.1, and A is the cross sectional area of flow.

The model considers the entrance and exit losses in the conduits, and handles flow control devices such as weirs, pumps and tide gates. Surge conditions are solved by applying the first-order correction based on the Hardy Cross method, which yields:

$$\left(\frac{\partial h}{\partial t} \right)_t = K \frac{\sum Q_t}{g(\Delta t)^2 \frac{A}{L}}$$

where K is a constant which introduces some under-relaxation in the system; a value of 0.25 is used in the model.

A is the cross-sectional area of the lines, and \sum is the summation of all lines entering the node.

(iv) Hydrograph Volume Method by Dorsch, HVM [3]:

The St. Venant momentum and continuity equations in the form shown on page 1 are applied in each sewer reach.

The backwater effects are considered, which means that the sewer system is simulated as an interdependent network and the effect of every network element on the remaining elements is taken into account. The manholes simulated as nodal points are handled analogously by means of energy and continuity equations. Using an implicit scheme, the numerical solution of the entire equation system is carried out using an iterative technique. The model simulates lateral flow, but it does not consider manhole storage. It handles retention basins by applying a reservoir routing technique.

The implicit solution scheme is more stable than the explicit one, while the method of characteristics gives the most accurate results. There is no indication of the difference in accuracy between the three models. However, the computing time should be considered if any comparison is done.

The model was applied several times for practical systems and good results have been experienced upon verification.

(v) Illinois Storm Sewer System Simulation Model (ISS Model) [4]:

The St. Venant equations for continuity and momentum are used. The lateral flow term is not included and it is assumed that inflow of storm water into the sewer system occurs only at discrete model points. This is, of course, justified for larger areas and equivalent watersheds. The equations are solved numerically by an explicit first-order characteristic scheme. Backwater effects are considered and the reservoir type junction is modelled where manhole storage is taken into account. Energy and continuity equations are formed for each manhole and the entire system is solved simultaneously at each time step. The model handles circular sewers only and it assumes that there are no more than three sewers joined together at a manhole.

The model was tested for a typical case and the results look very promising. A user's manual is available and the authors are presently expanding the model to handle surcharge conditions.

(vi) Massachusetts Institute of Technology Model, MIT [5]:

This model uses the kinematic wave equations which are the continuity equation and an approximate form of the momentum equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial X} = q$$

$$Q = \alpha A^m$$

where α and m are coefficients estimated from the Manning formula.

Table 1 summarizes the comparison of these routing models. With the fast progressing development in numerical techniques and high-speed computers, there is no limit for sophistication. However, the effect of the degree of sophistication for simulating the flows on the design and analysis of systems is still questionable.

For future analysis of the models, the HVM model can be considered as the most complex, compared with the SWMM, the WRE and the ISS models. The last three models will be available through the University of Florida. The comparison should be based mainly on accuracy and computing time. It should be noted that neither conduit shapes nor the structures considered in each model should have a considerable weight in the comparison. Simple modifications can be added to include conduit shapes or structure types missing in any of the models.

TABLE 1. COMPARISON OF ROUTING MODELS

MODEL	ROUTING TECHNIQUE	INTEGRATION SCHEME	BACKWATER EFFECTS	SURCHARGE	MANHOLE STORAGE
MWIS	Muskingum combined with the momentum equation with the inertia terms excluded		No	No	No
SWMM of EPA	Quasi-steady dynamic-wave approximation of the St. Venant equation	Implicit for continuity explicit for momentum Newton Raphson	No	No	No
WRE	$\frac{\partial Q}{\partial t} = -gAS_f + 2V \frac{\partial A}{\partial t} + V^2 \frac{\partial A}{\partial x} - gA \frac{\partial h}{\partial x}$ $\frac{\partial h}{\partial t} = \frac{\sum Q_t}{A_{st}}$	Explicit modified Euler method	Yes	Yes	Yes
HVM	St. Venant equation with lateral flow	Implicit scheme	Yes	Yes	No
ISS	St. Venant equations without lateral flow	Explicit first order characteristics scheme	Yes	No	Yes
MIT	$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$ $Q = \alpha A^m$			No	

TABLE 1. (CONT'D)

DESIGN OF SEWERS	CONDUIT SHAPES HANDLED	STRUCTURES CONSIDERED	AVAILABILITY	REMARKS
It has an optimization technique	Circular & Trapezoidal	None	nonproprietary	
No	Circular, Semi-elliptical, egg shaped	Pumps, flow dividers, Internal storage units (weirs & orifices)	nonproprietary	
No	Rectangular, circular, horseshoe, basket handle, egg shape, trapezoidal	Weirs, pumps, tide gates, orifices	proprietary	Studied presently by the University of Florida
No	Any shape, by inputting the area-depth relationship	Retention rectangular basins, weirs	proprietary	
Yes	Circular .	None	nonproprietary	Studies are carried on to add a sur- charge subroutine
			proprietary	

2. COMPARATIVE ANALYSIS OF WATER QUALITY MODELS

2.1 Basic Equations

2.1.1 Steady pollution load

An early attempt to model storm water quality was proposed by Stanley [6]:

$$B_r = \frac{(Q_r + Q_s) B_{sr} - Q_s B_s}{Q_r} \quad (1)$$

where: B_r = apparent BOD of storm flow during storm period, mg/l

B_s = average dry weather BOD received at treatment plant, mg/l

B_{sr} = average BOD received at plant during storm period, mg/l

Q_r = estimated average storm flow during storm period, cfs

Q_s = average annual sanitary flow, cfs.

However, such a model is incapable of predicting the actual quality of storm runoff water from basic data describing rainfall, demographic and watershed characteristics.

2.1.2 Unsteady pollution load, conceptual model [1]

Recent developments in analytical modelling of storm runoff water quality were achieved in different studies (EPA, University of Cincinnati, University of Florida) and adopted by other model builders (see Table 2). To date, these models are basically similar, with minor modifications in each particular case. The principal model formulation is as follows:

The total amount of a pollutant available for washoff by surface runoff at the beginning of storm is given by:

$$P_c = [F_c \times DD_L \times N_D] + [P_{oc} \times (1 - E)^n] \quad (2)$$

where: P_c = total pounds of pollutant c on land use L at the beginning of the storm,

F_c = pounds of pollutant c per pound of dust and dirt,

DD_L = rate of dust and dirt accumulation on a watershed of land use L in lb/day, $DD_L = dd_L \times (G_L/100) \times A_L$, where dd_L = rate of dust and dirt accumulation on a watershed of land use L in lb/day/100 feet of gutter, G_L = feet of gutter per acre in the watershed and A_L = area of the watershed,

N_D = number of dry days since last storm, if this is less than street sweeping interval, otherwise given by a different expression,

P_{oc} = total pounds of pollutant remaining on land at the end of last storm,

E = efficiency of street cleaning (0.6 to 0.95),

n = number of times the street has been swept since the last storm, $n = N_D/N_S$ = integer, where N_S = number of days between street sweeping.

The rate at which the pollutant is washed off the surface is given by:

$$M_p = P_t - P_{(t+\Delta t)} = A P_t (1 - e^{-br\Delta t})/\Delta t \quad (3)$$

where: M_p = rate of pollutant emission in given time interval (lb/hr),

P_t = the amount of pollutant remaining on street surface at time t,

$P_{(t+\Delta t)}$ = the amount of pollutant remaining on street surface at time (t+Δt),

Δt = the time interval (hr),

b = a constant which has the value of 4.6, assuming that a uniform rainfall of $\frac{1}{2}$ inch per hour would wash off 90% of the pollutant in one hour,

r = the runoff rate (inch/hr),

A = the fraction of solids available to runoff given by

$$A = C_1 + C_2 R^{C_3} \quad (4)$$

where C_1 , C_2 and C_3 are constants. In the case of pollutants other than solids, $A = 1.0$.

In the case of suspended and settleable solids equation (4) gives the emission rate of the pollutant from the street surface.

In the case of other pollutants such as BOD, it was found that some of the pollutant is tied up in the suspended and settleable solids. For example:

$$M_{\text{bod}}(t) = P_{\text{bod}}(t) \times (1 - e^{-brt}) + F_{\text{bod}}^I M_{\text{sus}} + F_{\text{bod}}^{II} M_{\text{set}} \quad (5)$$

where: F^I and F^{II} = the fractions of suspended and settleable solids, respectively.

Subscript bod = BOD

sus = suspended solids

set = settleable solids.

The contribution/retention of solids in the catch basin is determined by the settling velocity such that the fraction with a settling velocity higher than a critical velocity V_o will be retained in the catch basin. The removal of soluble pollutants from the catch basin was found to be

$$R = 100 \left[1.0 - e^{\left(\frac{-X}{1.6V} \right)} \right] \quad (6)$$

where: R = percent of soluble pollutant removed.

X = accumulated inflow volume to the catch basin

V = trapped volume of liquid in the catch basin.

In addition to solids contribution from street surfaces, the contribution from pervious areas can also be significant. This is given by the equation

$$A = (R) (K) (LS) (C) (P) \quad (7)$$

where: A = average soil loss over storm period
 K = the soil erodibility factor
 LS = the slope length gradient ratio
 C = the cropping management factor
 P = the erosion control practice factor.

The sediment load at any point in time can then be computed assuming either sediment concentration (as in the Penn. State University model) or sediment load (as in the modified EPA model by the University of Florida) to be proportional to the runoff flow rate.

2.1.3 Statistical models

A study by AVCO Economic Systems Corporation [7] adopted a statistical approach. In this study, a large quantity of data was collected (over 5,000 observations on 16 parameters) from 15 selected watersheds of different characteristics and correlated by regression analysis. Simplified linear equations were established for prediction of water quality parameters based on physical, demographic and land use data. The agreement between computed and measured results is satisfactory in some cases but poor in others.

A disadvantage of this model is that it may not be equally applicable to other cities without extensive recalibration requiring a large amount of data. Moreover, time variation of pollutant loading was not included in the final equations presented.

2.1.4 Semi-empirical model

In a recent study by Arnett et al [8] a model, somewhat semi-empirical in nature, was derived from the data obtained from the 1962-63 Cincinnati study, as follows:

$$M = K_1 + K_2 Q + K_3 V \quad (8)$$

where: $M(t)$ = $C \cdot Q$ = mass flow of pollutant in storm runoff
 per unit area at time t (lb/hour/acre)

$Q(t)$ = storm runoff per unit area at time t (cfs/acre)

$$V(t) = \int_0^t Q(t) dt = \text{cumulative volume of storm runoff per unit area since beginning of storm (ft}^3\text{/acre)}$$

$K_1, K_2, K_3 = \text{constants.}$

The values of K_1 , K_2 , and K_3 have been determined for different water quality parameters, including suspended solids, BOD, phosphate (PO_4) and nitrate (NO_3), and for different seasons. Although not evident from the report, it appears that the model gives reasonable agreement with the measured values, despite the simplicity.

2.2 Discussion

The above-noted models for surface runoff quality were calibrated for isolated areas and not well tested by verification. The EPA-SWMM model was calibrated using the data from Laguna St., but the verification in other cases shows the agreement between computed and measured results to be "fair to poor".

It can be noted from Table 2 that, in many areas, the models are considerably different from one another and improvements are evidently required. For instance, the Cincinnati study indicates 4.5% of the suspended solids contribute to BOD, the EPA model assumes 5%, and the U.S. Army model assumes a 10% contribution from suspended solids and 2% from settleable solids.

Furthermore, in most of the models only a limited number of parameters are simulated. The EPA model is only calibrated for suspended solids, BOD and coliforms.

It is, therefore, considered that even if the conceptual model of SWMM is adopted, a thorough analysis of all available data on surface runoff quality will be necessary. Available measurements should be compared against model predictions at least for order of magnitude validations.

Above all, it is essential to further calibrate the model, using the up-to-date information from Canadian sources such as results from sampling in Halifax, Montreal and Toronto. It is possible that, as a consequence of this analysis, some of the other models will be considered.

TABLE 2. WATER QUALITY MODELS

Model	Against what data is model calibrated?	Is model verified?	Time step used	Value of constant b	Pollutants included in model	Accumulated dust/dirt on surface
1. EPA-SWMM	Laguna St.	Yes, in several test cases, with only <u>fair to poor results</u>	10 min.	.46	Suspended solids, BOD, coli-form	As per Cincinnati study 1964
2. Cincinnati	Laguna St. Cincinnati 1962-63	None reported	15 min.	.46	Suspended solids	
3. U.S. Army STORM	None reported	None reported	1 hr.	.46	Solids BOD	
4. Shubinsky & Roesner		None reported		.46		

	Proportion of solids contributing to BOD	Is catch basin effect included?	Is routing of sediment in sewer considered?	Is BOD decay in sewer considered?	Does model consider amount of pollutant removal/concentration by overflow structure?	Is street cleaning practice considered?	Is contribution from vegetation considered?
1.	5% of suspended solids	Yes	Yes	Can be incorporated	No	Yes	No
2.		Yes	Yes	No	No	No	No
3.	10% of suspended solids 2% settleable solids	No	No	No	No	Yes	
4.					No		

	Is dry weather flow quality modelled?	Availability of dust/dirt to runoff	Is sediment contribution from pervious surfaces considered?
1.	Yes	for suspended solids $A_{sus} = 0.057 + 1.4R^{1.1}$	Yes, only in the later modification by University of Florida
2.	No	Not modelled	No
3.	No	$A_{sus} = 0.057 + 1.4 R^{1.1}$ and for settleable solids: $A_{set} = 0.028 + R^{1.8}$	No

Some of the main areas where improvement could help put the model into practical application in Canada are:

- 1) Ascertain the value of the constant b in the washoff rate, equation (3).
- 2) Ascertain the availability functions(s), equation (4).
- 3) Improve the estimates of dust/dirt fall, dd , particularly with regard to variation in amount b between cities and urban areas of different characteristics.
- 4) Improve estimates of pollutants, such as BOD and nitrate, on street surface, whether they are tied up in the form of solids or not.
- 5) Determine the street sweeping practices and cleaning efficiency of sweeping for different areas.
- 6) Another aspect to be examined is the inclusion of the efficiency of overflow control structures in concentrating solids in the through-flow stream, thus lessening the concentration in the overflow stream. Some studies on this subject have been carried out in England and for the updated EPA model. Conventional structures existing in older systems, as well as new ones such as that designed by J.F. MacLaren for the Toronto interceptor will be considered. During transport in the sewer or otherwise, the pollutant concentration in the storm water flow may be increased or decreased according to whether the pollutant is picked up/generated or settled out/decayed. A decay model of the Streeter-Phelps type is incorporated in the EPA-SWMM. Changes in DO and BOD concentrations are not considered in other models. The sensitivity of overflow quality to this aspect may be easily examined by comparisons.

3. LITERATURE SURVEY - URBAN RUNOFF QUALITY

3.1 General

3.1.1 Introduction

During the past few years, it has been well recognized that urban storm water runoff can contribute to a variety of problems, including direct pollution of receiving waters, overloading of treatment facilities, and impairment of sewers and catch basin functions. Generally, pollutants can enter into the urban runoff from three major sources: 1) the land surfaces, both pervious and impervious; 2) catch basins; and, 3) the sewers in the combined system.

Nevertheless, the land surface itself can be the most important contributor of a large number of pollutants. As the storm water runoff drains from urban land areas, it picks up accumulated debris, animal droppings, eroded soil, tire and vehicular exhaust residue, air pollutant fallout, heavy metals, fertilizers, de-icing compounds, pesticides and other chemical additives, decayed vegetation and many other known and unknown contaminants.

Previous studies provide much valuable information on the total problem of water pollution resulting from urban runoff. However, only a few studies have included data on both runoff quantity and quality in sufficient detail that quality of direct surface runoff can be evaluated as a function of runoff rates. Further, at present, sufficient information is not available on relationships between street surface contaminants, their pollutorial characteristics, and the manner in which they are transported during storm runoff periods [9, 10, 11].

3.1.2 Waste characteristics of urban storm water runoff

3.1.2.1 U.S. and other studies

Cincinnati, Ohio - One of the earlier studies of storm water pollution was performed in Cincinnati, Ohio, during the period between July, 1962 to September, 1963. In this study by Weibel et al [12], flow and quality measurements were taken for a 27-acre residential urban watershed served by separate sewer systems. The measured ranges for suspended solids,

volatile-suspended solids, BOD, and COD were 5-1200 mg/l, 1-290 mg/l, 1-173 mg/l, and 20-610 mg/l, respectively.

Durham, N.C. - Bryan [13], on the basis of his studies on a 1,067 acre urban watershed in Durham, N.C. came to the conclusion that the total weight contribution, on annual basis, of BOD by storm water was about equal to the sanitary wastewater effluent from secondary treatment at 85-95 percent efficiency. The contribution of total organic matter, as measured by chemical oxygen demand in storm water, was greater than that attributable to the discharge of sanitary wastewater. The total solids contribution by urban storm water was substantially larger than would be expected from average domestic sewage. In Table 3 [14] results of various studies conducted at other locations are compared with the results reported by Bryan.

Washington D.C. - In a study conducted in Washington, D.C., to investigate the waste characteristics of combined sewer overflows and separate storm water runoff, Buckingham et al [15] found that storm water runoff was highly contaminated. The waste characteristics of combined sewer overflows and separate storm water discharges based on the results of this study are shown in Table 4. Also shown are some of the same characteristics for domestic untreated sewage.

As can be seen from this table, the mean concentrations of BOD, total nitrogen, and total phosphate of combined sewer overflows are less than those of domestic sewage. This is to be expected because of the dilution of storm flows. The mean concentration of COD of the combined sewer overflows is between that of weak and medium domestic sewage. The mean concentration of total suspended solids of combined sewage overflows is approximately double the concentration found in strong domestic sewage. This may be due to the release of the material that has settled in the sewer between storms because of low flow velocities and which is now scoured out by the high storm velocities.

Minsk, U.S.S.R. - Pravoshinsky and Gatillo [16] indicated that the pollution of surface runoff from Minsk streets depended on a number of factors: the intensity of traffic (auto and pedestrian); type of cover of catchment; duration and intensity of rain; amount of dust deposition; antecedent dry period; and, quality and technology of town cleaning.

TABLE 3. COMPARISON OF STORM WATER QUALITY FROM AN URBAN DRAINAGE BASIN IN DURHAM, N.C. WITH RESULTS REPORTED BY OTHERS. [14]

Location		BOD (mg/l)	COD (mg/l)	Total Solids (mg/l)	Volatile Solids (mg/l)	Suspended Solids (mg/l)	Total Phosphate (mg/l)	Coliforms (MPN/ 100 ml)*	Chloride as NaCl (mg/l)
Durham, N. C. (urban stormwater)	Mean	14.5	179	2,730	298	—	0.58	30,000 F	12.6
	Range	2->232	40-600	274-13,800	20-1,110	—	0.15-2.50	7,000-86,000 F†	3.0-390
Cincinnati, Ohio (urban stormwater)	Mean	17	111	—	—	227	1.1	—	19.8
	Range	1-173	20-610	—	—	5-1,200	<0.02-7.3	500-76,000 F	5.0-705
Cincinnati, Ohio (rainfall)	Mean	—	16	—	—	13	0.24	—	—
Coshocton, Ohio (rural stormwater)	Mean	7	79	—	—	313	1.7	—	—
	Range	0.5-23	30-159	—	—	5-2,074	0.25-3.3	<2-56,000 F	—
Coshocton, Ohio (rainfall)	Mean	—	9.0	—	—	11.7	0.08	—	—
Detroit, Mich. (1949) (urban stormwater)	Range	96-234	—	310-914	—	—	—	25,000-930,000 T	—
Seattle, Wash. (urban stormwater)		10	—	—	—	—	4.3 max	16,100 F max	—
Stockholm, Sweden (urban stormwater)	Median	17	188	300	90	—	—	4,000 F	—
	Maximum	80	3,100	3,000	580	—	—	200,000 F	—
Pretoria, South Africa (residential park/ school)		30	29	—	—	—	—	240,000 F	—
(business and flat area)		34	28	—	—	—	—	250,000 F	—
Oxney, England	Maximum	100	—	—	—	2,045	—	—	—
		36	—	—	—	14,541	—	—	—
Leningrad, USSR									
Moscow, USSR	Range	18-285	—	—	—	1,000-3,500	—	—	—

* F = fecal; T = total.

† Range of means for 17-storm series for Durham, N. C.

TABLE 4. CHARACTERISTICS OF COMBINED SEWER OVERFLOWS, SEPARATE STORM WATER DISCHARGES AND DOMESTIC SEWAGE [15]

Constituent*	Combined Sewer Overflow		Separate Storm Water		Domestic Sewage		
	Range	Mean	Range	Mean	Strong	Medium	Weak
Biochemical Oxygen Demand	10-470	71	3-90	19	300	200	100
Chemical Oxygen Demand	80-1,760	382	29-1,514	335	1,000	500	250
Total Solids	120-2,900	883	338-14,600	2,166	1,200	700	350
Total Suspended Solids	35-2,000	622	130-11,280	1,697	350	200	100
Total Volatile Suspended Solids	10-1,280	245	0-880	145	275	150	70
Total Phosphate	0.8-9.4	3.0	0.2-4.5	1.3	20	10	6
Total Nitrogen	1.0-16.5	3.5	0.5-6.5	2.1	85	40	20
Ammonia	0-4.7	1.5	-	-	50	25	12
Total Coliform (1000 Counts/100 ml)	420-5,800	2,800	120-3,200	600	-	-	-
Fecal Coliform (1000 Counts/100 ml)	240-5,040	2,400	40-1,300	310	-	-	-
Fecal Streptococcus (1000 counts/100 ml)	1-49	17.2	3-60	21	-	-	-

* All in concentrations of mg/l unless otherwise specified.

Sartor and Boyd study - Sartor and Boyd [11] investigated the water pollution aspects of street surface contaminants from 12 cities in the U.S. and found that runoff from street surface was generally highly contaminated. Besides the conventional water pollution parameters, constituents such as chlorinated hydrocarbon, organic phosphate compounds, heavy metals, and polychlorinated biphenyls were also found. However, the major constituent of street surface pollutants was consistently found to be inorganic, mineral-like matter. Some of the results of this study are reproduced in Table 5. Also, it was noted that a great portion of the overall pollutorial potential was associated with the finer solids fraction of the street surface contaminants, as shown in Table 6. Moreover, the COD test was found to provide better estimates of oxygen demanding potential than the standard BOD test.

This is attributed to the fact that the standard BOD test may not determine the full BOD of the storm runoff, because the high solids concentration hampers bacterial growth and thus delays biodegradation.

APWA and AVCO Corporation studies - Recent studies conducted in Chicago and Tulsa by APWA [17] and AVCO Corporation [7] provide much valuable information on the rate at which pollutants accumulate on an urban watershed. The data are reported in dissimilar forms (see Tables 7 and 8) which makes it difficult to generalize. Nevertheless, results of these studies give an indication of the magnitude of pollutant build-up for different land uses. In order to compare the results of these studies, Roesner et al [18] converted the data into a comparable form as shown in Table 9. It is evident from a comparison of Tables 8 and 9 that, while the Chicago data are consistently lower than the Tulsa data, the accumulation rates are similar in commercial areas except for PO_4 , and also the accumulation rate of pollutants in an urban watershed varies significantly with land use, which confirms the findings of other studies [9]. Furthermore, results of the Chicago study [17] showed that catch basins, which hold a large fraction of solids during periods of low flow, may be one of the largest single sources of pollution from storm water flows.

The differences between results of these two studies may be partly attributed to the fact that in the APWA study [17], which was

TABLE 5. CONSTITUENTS IN STREET SURFACE POLLUTANTS [11]

MEASURED CONSTITUENTS	WEIGHTED MEANS FOR ALL SAMPLES (lb/curb mile)
Total Solids	1400
Oxygen Demand	
BOD ₅	13.5
COD ₅	95
Volatile Solids	100
Algal Nutrients	
Phosphates	1.1
Nitrates	.094
Kjeldahl Nitrogen	2.2
Bacteriological	
Total Coliforms (org/curb mile)	99×10^9
Fecal Coliforms (org/curb mile)	5.6×10^9
Heavy Metals	
Zinc	.65
Copper	.20
Lead	.57
Nickel	.05
Mercury	.073
Chromium	.11
Pesticides	
p,p-DDD	67×10^{-6}
p,p-DDT	61×10^{-6}
Dieldrin	24×10^{-6}
Polychlorinated Biphenyls	1100×10^{-6}

TABLE 6. FRACTION OF TOTAL CONSTITUENT ASSOCIATED WITH EACH PARTICLE SIZE RANGE (% by weight) [11]

	<43 μ	43 μ \rightarrow 246 μ	>246 μ
TOTAL SOLIDS	5.9	37.5	56.5
BOD ₅	24.3	32.5	43.2
COD	22.7	57.4	19.9
Volatile Solids	25.6	34.0	40.4
Phosphates	56.2	36.0	7.8
Nitrates	31.9	45.1	23.0
Kjeldahl Nitrogen	18.7	39.8	41.5
Heavy Metals (all)	51.2		48.7
Pesticides (all)	73		27
Polychlorinated Biphenyls	34		66

TABLE 7. APWA FINDINGS ON RATE OF POLLUTANT BUILDUP ON URBAN WATERSHEDS [17]

Amount of Dust and Dirt and Strength of BOD by Land Use

<u>Land Use</u>	<u>Amt. of D/D by land use lb/day/100 ft of curb</u>	<u>BOD of D/D mg/g</u>
Commerical	3.3	7.7
Industrial	4.6	3.0
Multiple family	2.3	3.6
Single family residence	<u>0.7</u>	<u>5.0</u>
Assumed weighted average	1.5	5.0

Amount of Pollutant by Type of Land Use

<u>Item</u>	<u>Single Family</u>	<u>Multiple Family</u>	<u>Commercial</u>
Water soluble (mg/g)	6.0	5.6	12.4
Volatile Water Soluble (mg/g)	3.8	3.4	6.9
BOD (mg/g)	5.0	3.6	7.7
COD (mg/g)	40	40	39
PO ₄ (mg/g)	.05	.05	.07
N (mg/g)	.48	.61	.41
Total plate counts/g (x 1000)	10,900	18,000	11,700
Confirmed coliform/g (x 1000)	1,300	2,700	1,700
Fecal enterococci/g	645	518	329

TABLE 8. AVERAGE DAILY LOADS PER MILE OF STREET
(TULSA, OKLAHOMA) [7]

Test Area	Total Street Miles	Average Load: lb /day/mile of street				
		BOD	COD	Total Solids	Organic Kjeldahl Nitrogen	Soluble Orthophosphate
<u>Residential</u>						
3	14.87	1.41	11.46	120	0.26	0.34
5	16.32	2.80	21.43	43	0.11	0.13
7	6.84	1.20	7.20	63	0.12	0.10
8	6.97	2.72	20.89	69	0.12	0.21
9	3.11	1.12	13.09	47	0.07	0.11
11	49.05	1.60	13.29	66	0.08	0.15
13	5.58	2.58	15.16	81	0.25	0.20
15	2.06	2.47	8.67	56	0.07	0.17
<u>Commerical</u>						
2	7.41	2.54	15.12	92	0.32	0.29
10	12.99	2.10	20.44	82	0.16	0.13
12	3.39	4.53	25.47	113	0.22	0.30
<u>Industrial</u>						
1	11.46	4.85	41.10	838	0.41	1.30
4	28.40	3.98	29.29	175	0.28	0.30
6	12.24	1.70	12.73	49	0.09	0.13
<u>Average Values</u>						
Residential		1.98	13.9	63.1	0.14	0.18
Commercial		3.06	20.3	95.7	0.23	0.24
Industrial		3.51	27.7	354.	0.26	0.57

based on 18 test areas in Chicago, no measurements were made of the quality of the storm water runoff itself. The estimation of pollutant accumulation rate was based solely on measurements and sampling of street sweeping, whereas for the Tulsa study [7] storm water runoff was sampled from 15 watersheds of varying land use activities. It is evident that the Chicago study may have considerably underestimated the pollution loadings of urban runoff by excluding all the miscellaneous leaks and flows which are not measured in street dust and dirt.

TABLE 9. AVERAGE DAILY LOADS PER MILE OF STREET (CHICAGO, ILLINOIS) [18]

Land Use	Average Load: lb/day/mile of street			
	BOD	COD	N	PO ₄
Single Family Residential	0.36	2.95	0.03	0.004
Multiple Family Residential	0.87	9.70	0.15	0.012
Commercial	2.70	13.6	0.14	0.024
Industrial	1.45			

3.1.2.2 Canadian studies

Halifax studies - Waller [19] collected valuable data on composition of combined sewage, surface runoff, and effluent from a combined sewage retention tank as a part of a comprehensive study conducted in Halifax, N.S. to determine the pollutional impact of combined sewage overflows. Mean values of constituents in sewage, combined sewage, and surface runoff are listed in Table 10 and these values were found to be in close agreement with those reported elsewhere. The flow and quality data for this study were collected from a 168 acre residential watershed drained by a combined sewer system. Surface runoff samples were taken at three sites within the study area. Rainfall was recorded by five standard rain gauges, including one gauge located in the watershed.

In another recent study conducted in Halifax by Waller and Coulter [20] to investigate the characteristics of the winter runoff and

TABLE 10. ARITHMETIC MEAN VALUES OF CONSTITUENTS IN SEWAGE, COMBINED SEWAGE, AND SURFACE RUNOFF IN HALIFAX [19]

<u>CONSTITUENT</u>	SEWAGE	COMBINED SEWAGE	SURFACE RUNOFF		BEECH ST.
	24-hr Mean DWF		QUINPOOL RD.	CAMBRIDGE ST.	
Suspended Solids (mg/l)	110	195	132	59	98
Volatile Suspended Solids (mg/l)	92	115	35	18	36
BOD ₅ (mg/l)	130	94	25	42	68
Total Coliform (10 ⁶ per 100 ml)	45	55	4.2	5.6	-
Fecal Coliform (10 ³ per 100 ml)	3,165	1,700	10	10	-
Fecal Strep. (10 ³ per 100 ml)	265	180	28	19	-

TABLE 11. RATE OF POLLUTANT ACCUMULATION IN HALIFAX [20]

<u>LAND USE</u>	TOTAL AMOUNT OF SOLIDS IN 1b/CURB MILE	AMOUNT OF POLLUTANT IN mg/gram OF SOLIDS		
		<u>Susp. Solids</u>	<u>N</u>	<u>PO₄</u>
1. Residential	4555	950	.08	.05
2. Commercial	1660	955	.03	.03

snowmelt, an attempt was also made to determine the rate of solids accumulation on the street surfaces. Samples of solids accumulated in gutters and on street surfaces were collected, weighed, and analysed on three occasions during the winter season at four sampling sites located in the residential and the light commercial areas. Results from these limited number of samples could provide only an estimate of the accumulated solids. However, chemical analyses of solids fractions gave an indication of the pollutant composition of the street dust and dirt as shown in Table 11. Higher values of total solids found in this study clearly reflect the effect of street sanding and salting during the winter season. The low magnitude of total solids in the commercial area may be a result of the fact that only one sampling site was located within that particular area. Hence, these numbers should be used with caution. In this study, no attempt was made to determine the daily accumulation rate for street dust and dirt.

Winnipeg - A monitoring program was conducted by the city of Winnipeg in the summers of 1969 to 1971, to determine the effect of combined sewer overflows on the receiving water body [21]. The flow and quality measurements taken from six districts, all having combined sewer systems, showed very high values for the suspended solids, BOD and total phosphates. Ranges for these parameters are shown in Table 12 for five of the districts. Also shown in Table 12 is the total drainage area and land use classification for each district.

North York, Toronto - Analysis of storm water runoff samples collected from a 48 acre suburban residential neighbourhood of Toronto, in a study currently underway by James F. MacLaren Limited, has clearly indicated the highly contaminated nature of urban surface runoff. Table 13 shows the observed range of concentrations for various pollutional parameters sampled during the three month period from April to June, 1974 [22].

East York, Toronto - In a recent study performed by the Borough of East York [23], flow and quality measurements were taken from May to September, 1974. The concentration of all quality constituents except for the BOD were found to lie within the ranges shown in Table 13. Much higher values

TABLE 12. QUALITY MEASUREMENTS RECORDED IN WINNIPEG

<u>District</u>	<u>Drainage Area Acres</u>	<u>Land Use Type</u>	<u>Suspended Solids mg/l</u>	<u>BOD mg/l</u>	<u>Total PHOSPHATE mg/l</u>
1. Bannatyne	575	50% Commercial 50% Residential	154-9294	25-1720	0.4-53.0
2. Linden	510	Residential	80-2585	51-1325	
3. Aubrey	1300	Residential	186-6720	14-502	
4. Ash	2100	Residential	72-2805	30-550	
5. Orleans	1670	20% Undeveloped 80% Mixture of Residential and Industr- ial.	144-4952	30-2400	1.6-66
6. Mission	2900	Industrial with large open spaces			

TABLE 13. OBSERVED RANGE OF POLLUTANT CONCENTRATIONS IN SURFACE RUNOFF
(mg/l) MEASURED IN NORTH YORK, TORONTO

<u>Pollutant</u>	<u>Observed Range</u>	<u>Mean</u>	<u>No. of Samples</u>
Solids			
Total	300-1200		13
Suspended	<15-770	110	27
Dissolved	100-1170		8
BOD ₅	0.6-110	13.2	35
COD	<20-920	95	33
Total Kjeldahl			
Nitrogen	0.5-19	3.5	42
Nitrate	0.2-4	2.2	42
Nitrite	<0.02-0.26	0.1	42
Free Ammonia	0.1-3.3	0.5	42
Total Phosphate	0.1-1.6	0.3	42
Sulphate	12-200	105	36
Chloride	17-290	166	42
Lead	0.03-1.8		35
Sodium	8-137	68	42
Potassium	1.3-15	5.8	42
Coliform (MPN/100 ml)			
Total	100-82000	14800	13
Fecal	10-7300	1330	12
Enterococcus	20-4200	1100	12

for BOD, in the range of 4-320 mg/l, were recorded. In this study, data were collected only for low intensity storms from a 40 acre residential area drained by a separate sewer system.

Montreal - In a monitoring program conducted in Montreal [24], flow and quality measurements were taken for the Curotte-Papineau catchment during August and September of 1973. This watershed comprises about 2883 acres and is drained by a combined sewer system. About 48% of the area is residential, 40% industrial, 8% commercial, and the remainder is open land and parks. The population density of the area is approximately 37.3 persons/acre. The flow and quality measurements were recorded by using automatic samplers taking samples at five minute intervals. No rain gauge was located within the watershed itself. However, rainfall data from three rain gauges around the catchment were available and were used for computing the rainfall intensity for various storms. Water samples were collected only during six storm events, whereas flow was recorded for a total of 11 storms which occurred during August and September, 1973. These water samples were analyzed for BOD, suspended solids and coliforms.

The ranges recorded for the BOD, suspended solids, and coliforms were 30-280 mg/l, 25-1450 mg/l, and 5×10^4 - 3.1×10^6 MPN/100 ml, respectively. Moreover, water samples were also collected for other watersheds in Montreal in order to determine the quality characteristics of the dry weather flow. However, for all these cases, flow and quality were not monitored on a continuous basis, and hence the data are of little value for modelling purposes.

3.1.3 Discussion

The results of studies presented above clearly indicate that a wide variation can be expected in the magnitude of different quality constituents from place to place and from time to time, depending upon a number of factors. These factors include land use activities, antecedent conditions, precipitation characteristics, street cleaning practices, etc. Moreover, it has been found that usually data collected on the quality of combined sewer overflows and storm water runoff are reported in average

concentration of the runoff, whereas the pollution potential of these sources can be better evaluated when data are presented in terms of mass discharge rates, such as lb/day or lb/yr/acre. Generally, mass emission rates are more significant for the long term effects, and concentrations are perhaps more significant for the short term shock effects. However, for planning purposes, data are required in terms of daily pollutant accumulation rates for a particular land use classification (lb/day/curb mile), in order to determine the total pollution loadings from an urban catchment.

Further, it appears that at present adequate information related to the input data generally required for modelling purposes does not exist for most of the Canadian watersheds. Moreover, in previous studies no attempt was made to collect information about the street cleaning practices and to evaluate the cleaning efficiency of the equipment usually used. However, it has been well recognized that city works practices can considerably control storm water runoff pollution.

3.2 Urban Runoff Quality Modelling

3.2.1 Analytical models

3.2.1.1 Steady pollution load model. Within the past few years, several attempts have been made to model urban storm water runoff quality. Such an attempt by Stanley [25] resulted in a rather simplified equation:

$$B_r = \frac{(Q_r + Q_s) B_{sr} - Q_s B_s}{Q_r} \quad (1)$$

where: B_r = apparent BOD of storm flow during storm period, mg/l
 B_s = average dry weather BOD received at treatment plant, mg/l
 B_{sr} = average BOD received at plant during storm period, mg/l
 Q_r = estimated average storm flow during storm period, cfs
 Q_s = average annual sanitary flow, cfs.

However, such a steady pollution load model is incapable of consistently predicting the actual quality of storm runoff from particular storm events, which depends on basic data such as rainfall intensity, demographic and watershed characteristics.

3.2.1.2 Storm water simulation models. Analytical modelling of storm water runoff quality has received much attention in recent studies and, at present, the following four comprehensive models are available:

1. EPA's Storm Water Management Model (SWMM)
 - a) Old Runoff Model developed by Metcalf and Eddy
 - b) New Runoff Model developed by Water Resources Engineers Inc.
 - c) New Runoff Model revised by University of Florida
2. U.S. Army Corps of Engineer's Model (STORM)
3. University of Cincinnati Model
4. Hydrocomp Simulation Program

The models developed by the U.S. EPA [1] and the University of Cincinnati [26] are essentially the same except for the integral instead of stepwise solution used in the latter. The University of Florida [28] model is a more recent version of the EPA's Storm Water Management Model and again differs very little from the original EPA version. The old runoff model (ORM) is the runoff quality model originally developed by Metcalf and Eddy and presently included in most of the SWMM versions [27]. The new runoff model (NRM) was developed by Water Resources Engineers Inc. and has been further modified by the University of Florida.

In both the Hydrocomp Simulation Program [29] and the STORM model [30], storm water quality is computed with nonlinear functions of land use and storm water runoff similar to the formulation of the EPA's Storm Water Management Model.

(a) Environmental Protection Agency Storm Water Management Model

This model, developed by the EPA, is found to be one of the most comprehensive mathematical models for the simulation of storm and combined sewerage systems. It computes the combined storm and sanitary runoff from several catchments and routes the flows through a converging branch sewer network. It can model suspended solids and settleable solids, BOD, COD, coliform bacteria, nitrogen, phosphorus, and oil and grease. However, the model is limited to the simulation of single runoff events. In this model, storm water quality is computed from nonlinear functions considering different land uses. The formulations consider the pollutant accumulation between storm events, street sweeping practices and the rate of storm water runoff. The combined wastewater quality is routed through the sewers using pure advection, with scour and deposition for suspended solids, and decay for biochemical oxygen demand.

(b) U.S. Army Corps of Engineers STORM Model

The Storage, Treatment and Overflow Model (STORM) of the Corps of Engineers Hydrologic Center, is intended primarily for the evaluation of storm water storage, and treatment capacity required to reduce untreated overflows below specified values. The model can simulate hourly storm water runoff and quality for a single catchment for several years. Five water quality constituents are computed for different land uses: suspended and settleable solids, biochemical oxygen demand, nitrogen and phosphorus. Coliform organisms are not simulated by STORM. Storm water runoff quality is computed with land use, and storm water runoff similar to the formulation of the EPA Storm Water Management Model. This model does not route the storm water runoff and quality in a sewer or channel network.

The model depends on several empirical coefficients for both storm water runoff and quality computations. The model appears useful primarily for preliminary planning studies to estimate approximate magnitudes of untreated storm water overflows for various combinations of storage and treatment capacities. Further, this model is limited in its application to storm water drainage systems, since it does not consider dry weather flow and quality. The model also computes the quantity and

quality of runoff from the nonurban areas of the watershed in a similar manner to that from the urban area.

Methods of computation - Following are the basic equations used in different models to estimate the pollution loads resulting from urban storm water runoff:

$$P = A_v P_o e^{-b \cdot r \cdot \Delta t} \quad (2)$$

$$\Delta P = P_o - P \quad (3)$$

where: P = mass of pollutant on surface at the end of time step, Δt

ΔP = mass of pollutant removed during time step, Δt

P_o = the amount of pollutant on street surface at the start of storm. $P_o = P$ at the start of subsequent time steps.

r = the runoff rate (inch/hr)

Δt = the time interval (hr)

b = a constant which has the value of 4.6, assuming that a uniform runoff of 1/2 inch per hour would wash off 90% of the pollutant in one hour.

A_v = the fraction of solids available to runoff, given by

$$A_v = C_1 + C_2 r^{C_3}$$

where C_1 , C_2 , and C_3 are constants. In the case of pollutants other than solids, $A_v = 1.0$.

In the formulation of equation (2), it was assumed that the amount of a particular pollutant washed off in any given time interval during a storm event would be proportional to the amount of the pollutant remaining on the ground.

The total amount of a pollutant accumulated on the street surface prior to the storm can be computed from the following relationship:

$$P_o = N_s \times DD_L \times F_p \times [1 + \sum_{i=1}^n (1-E)^i] \quad (4)$$

where: N_s = number of days between street cleanings
 DD_L = dust and dirt accumulation rate on a watershed of land use L in lb/day
 E = efficiency of street cleaning
 n = number of times the street has been swept since the last storm, N_D/N_s = integer n
 N_D = number of dry days before storm event
 F_p = mg of pollutant per gm of dust and dirt.

Both the EPA Storm Water Management and STORM models used the following equations for determining the factor A_v for suspended and settleable solids:

$$A_{sus} = 0.057 + 1.4r^{1.1} \quad (5)$$

$$A_{set} = 0.028 + 1.0r^{1.8} \quad (6)$$

However, a different technique was used in the old runoff model (ORM) for the computation of suspended solids. The following equation, used by the ORM and not documented in Vol. I [1], was based on specific experience modelling Laguna St., San Francisco.

$$\Delta P = AREA \times (A \times E + B \times E^D) \times cc \times P_o/P_i \quad (7)$$

where: ΔP = pounds SS removed during time step, Δt
 $AREA$ = subcatchment area in acres
 A = $0.004 \Delta t$ (Δt in minutes)
 B = $0.0025 \Delta t$
 D = $2.6 - 1.25 r^{\frac{1}{2}}$
 E = $100 r$
 r = runoff in inches/hour

$$cc = \text{"removing coefficient"} = 0.90 - 0.0025 \Delta t$$

$$(0.25 \leq cc \leq 0.90)$$

P_o = mass of SS on surface at beginning of time step, Δt

P_i = mass of SS on surface at beginning of the storm (beginning of simulation).

In addition to equations (2) and (3), the above equation has also been included in the new runoff model by the University of Florida. The computation for SS can be made by using either of the two techniques. In the new runoff model developed by WRE, equations (2) and (3) are solved in a somewhat different way. Also, the availability factor, A , is not considered in the WRE model and lower default values are used for suspended solids.

The STORM model also allows for the use of default values for nonurban areas, as shown in Table 14. These values are found to be higher, by several orders of magnitude than those reported by others for similar areas [31]. Table 15 summarizes the results of a study of several rural watersheds in the U.S.A. (Minnesota, Wisconsin, and North Carolina). Similar results have also been reported by other investigators, such as Sawyer [32], Sylvester [33], Engelbrecht [34], and Owens [35]. The pollutant loading rates shown in Table 15 cannot be directly compared with the default values given in the STORM model, since each estimate is based on different land use patterns and activity within the same general classification (such as open space, pastures, farm land and forest).

Data reporting solids loading rates from nonurban areas are very limited. A 173-acre cultivated site in eastern South Dakota was sampled by McCarl [36] in 1970. The total annual load of suspended solids computed for this area (for the 1970 runoff season) was found to be 2040 lb/acre/year, which is equivalent to 5.6 lb/day/acre, on an average. Dornbush et al [37], in a similar study during 1971-72 in South Dakota, estimated annual losses of sediment from agricultural and rural land areas. The maximum solids loading rate recorded was 1000 lb/acre/year, (i.e. 2.7 lb/day/acre). Slaymaker et al [38] made an estimate of sediment load from agricultural land in northwestern U.S.A. and indicated that

TABLE 14. DEFAULT VALUES FOR NONURBAN POLLUTANT LOADING RATES*

Nonurban Land Use	lb of Pollutants/day/acre		
	BOD	N	PO ₄
Open Space and Rural	.030	.007	.003
Agricultural (pastures)	3.100	.500	.350
Agricultural (farming)	.020	.230	.070
Forests	.01	.002	.00002

* Values obtained from Hydrocomp, Inc., Palo Alto, Calif.

TABLE 15. POLLUTANT ACCUMULATION RATES IN NONURBAN RUNOFF IN THE U.S.A.

Land Use	lb of Pollutants/day/acre		
	BOD	N	P
Open Space/Rural Grass-land	-	.00073	.000024
Agricultural (pastures)	.036 ^a	.0118 ^a	.0052 ^a
Agricultural (farming)	-	.0143 ^b	.00033 ^b
Forests	-	.0047 ^c	.00031 ^c

a) Average value of six pasture lands sampled in North Carolina

b) Average value based on three types of crops (corn, oats and alfalfa) and 200 lb fertilizer/acre added to all corn area and 150 lb/acre to oats and alfalfa.

c) Average value of four watersheds in Minnesota between August and November.

0.84 tons/acre/year (equivalent to 5.1 lb/acre/day) of potential solids loading is to be expected from a well-grazed pasture. Walker and Wadleigh [39] discussed water pollution as it relates to land runoff, and estimated that the sediment yield of the Mississippi River Basin averages 390 tons/sq mile/year, which is equivalent to 3.7 lb/acre/day.

Whereas these studies indicate the range of values of solids loading from nonurban runoff, two important factors must be borne in mind. First of all, it is to be noted that a considerable scale problem exists in these analyses in that, for estimation of solids loading from large areas, (such as river basins) geology, physiography and climate are the dominant factors. The values of solids loading rates from small nonurban watersheds are governed by the type of land characteristics, as determined by the type of land use, extent of vegetative cover and land topography. The resulting effect, on an areal basis, is that the values estimated for large watersheds are lower than those estimated on a micro level (subwatershed analysis).

Secondly, the values cited herein (range 2.7 lb/acre/day to 5.6 lb/acre/day) are in the higher range of values for solids loading and should, therefore, be regarded as the potential loading rates, representing just about the worst condition.

In the Storm Water Management study, it was found that the BOD associated with suspended solids may range from 3 to 10 percent of the suspended solids load and, hence, a value of 5 percent was included in the model. But the U.S. Army study [32] included BOD tied with both suspended solids and with settleable solids and the following equations were used for BOD, nitrogen and PO_4 :

BOD:

$$M_{bod} = P_{bod} \times (1 - e^{-br\Delta t})/\Delta t + 0.1 M_{sus} + 0.02 M_{set} \quad (8)$$

Nitrogen:

$$M_{nit} = (1 - e^{-br\Delta t})/\Delta t + 0.045 M_{sus} + 0.01 M_{set} \quad (9)$$

PO_4 :

$$M_{PO_4} = P_{PO_4} \times (1 - e^{-br\Delta t})/\Delta t + 0.0045 M_{sus} + 0.01 M_{set} \quad (10)$$

The new runoff model of SWMM, updated by the University of Florida, also includes the above equations. However, a value of 5% is used instead of 10% for insoluble BOD tied with the suspended solids. In both SWMM and STORM, the APWA study [17] results for the dust and dirt accumulation rates are used as default values in case other suitable values for a particular watershed are not available. Table 16 shows the default values programmed in the SWMM for computing dust and dirt accumulation rates, coliform bacteria, and composition of dust and dirt.

The Storm Water Management Study [1] also considered the BOD contribution of solids in catch basins by using the following empirical equation developed from the results of APWA study [17]:

$$R = 100 \left[1.0 - e^{\left(\frac{-X}{1.6V} \right)} \right] \quad (11)$$

where: R = percent of catch basin source pollution removed
X = cumulative inflow to catch basin (gal)
V = trapped volume of liquid in basin before storm (gal).

In addition to solids contribution from the street surface, the contribution from pervious areas can also be significant and can be predicted by the universal soil loss equation which is as follows [40]:

$$A = (R) (K) (LS) (C) (P) \quad (12)$$

where: R = the rainfall factor
K = the soil erodibility factor
LS = the slope length gradient ratio
C = the cropping management factor, and
P = the erosion control practice factor.

Heany and Huber [28] demonstrated the use of the above equation to predict the total erosion from a given land area for a single storm event and also incorporated it into the modified version of the Storm Water Management Model. The above equation is also used in the STORM to calculate land surface erosion.

TABLE 16. DEFAULT VALUES FOR DUST AND DIRT ACCUMULATION USED IN SWMM^a

<u>Land Use</u>	<u>Dust and Dirt Accumulation lb/day/100 ft Curb</u>	<u>Coliforms^c</u>	<u>mg Pollutant per gm of Dust and Dirt</u>						
			<u>Susp. Solids</u>	<u>Sett. Solids</u>	<u>BOD</u>	<u>COD</u>	<u>N</u>	<u>PO₄</u>	<u>Grease^d</u>
1. Single Family	0.7	1.3×10^6	1000.0 (111.0) ^e	100.0	5.0	40.0	0.48	0.05	1.00
2. Multiple Family	2.3	2.7×10^6	1000.0 (80.0)	100.0	3.6	40.0	0.61	0.5	1.00
3. Commercial	3.3	1.7×10^6	1000.0 (170.0)	100.0	7.7	39.0	0.41	0.7	1.00
4. Industrial	4.6	1.0×10^6	1000.0 (67.0)	100.0	3.0	40.0	0.43	.03	1.00
5. Undeveloped ^b or Park	1.5	0.0	1000.0 (111.0)	100.0	5.0	20.0	0.05	.01	1.00

a - Most values are based on 1969 APWA report [17], and included in NRM (University of Florida).

b - Values for undeveloped and park lands are assumed.

c - Units for coliforms are MPN/gram.

d - All values are assumed.

e - Values used in NRM (WRE).

Model application:

(a) EPA Storm Water Management Model - The Storm Water Management Model was calibrated using the data from Laguna Street, San Francisco [1] and Figure 1 shows the comparison with the reported results for the March 10, 1967 storm. It is indicated that agreement at peak flows is better than at the low flows, which means that the total pounds of pollution are being modelled satisfactorily. A similar comparison between the reported and computed total coliforms is shown in Figure 2. However, the verification of the model in other cases such as Cincinnati, Washington, D.C., and Philadelphia [1] showed the agreement between computed and measured results to be "fair to poor". For all these cases, data for combined sewers were applied to the model for testing and verification.

The data collected for the Boulevard combined sewer catchment in Atlanta were also used for testing the SWMM [41]. The storm event of June 20, 1973 was simulated. Rainfall data from three rain gauges within Metropolitan Atlanta were available. However, none of them was located in the catchment. Figures 3, 4 and 5 show the results of the SWMM application versus measured values. Computed BOD is somewhat lower than measured values and computed suspended solids are much lower. No erosion was modelled due to lack of local data for the Universal soil loss equation. This accounts for the low values for SS and accounts for the somewhat lower BOD values; the additional SS due to erosion would have contributed to the BOD load.

Also, the SWMM was tested for the data collected in the Stevens Avenue district, Lancaster [27]. Storm events of March 22, 1972, and November 29, 1971 were simulated. For both of the storm events, a complete set of measurements was available. Figures 6 and 7 show the results of the computer simulation, along with quality and quantity measurements. It can be seen that agreement between the computer simulation and the actual measurements of flow is fairly good, considering the degree of accuracy of the input data as well as that of the measurements. The agreement between the computed quality and measured quality parameters is not as good as for flows.

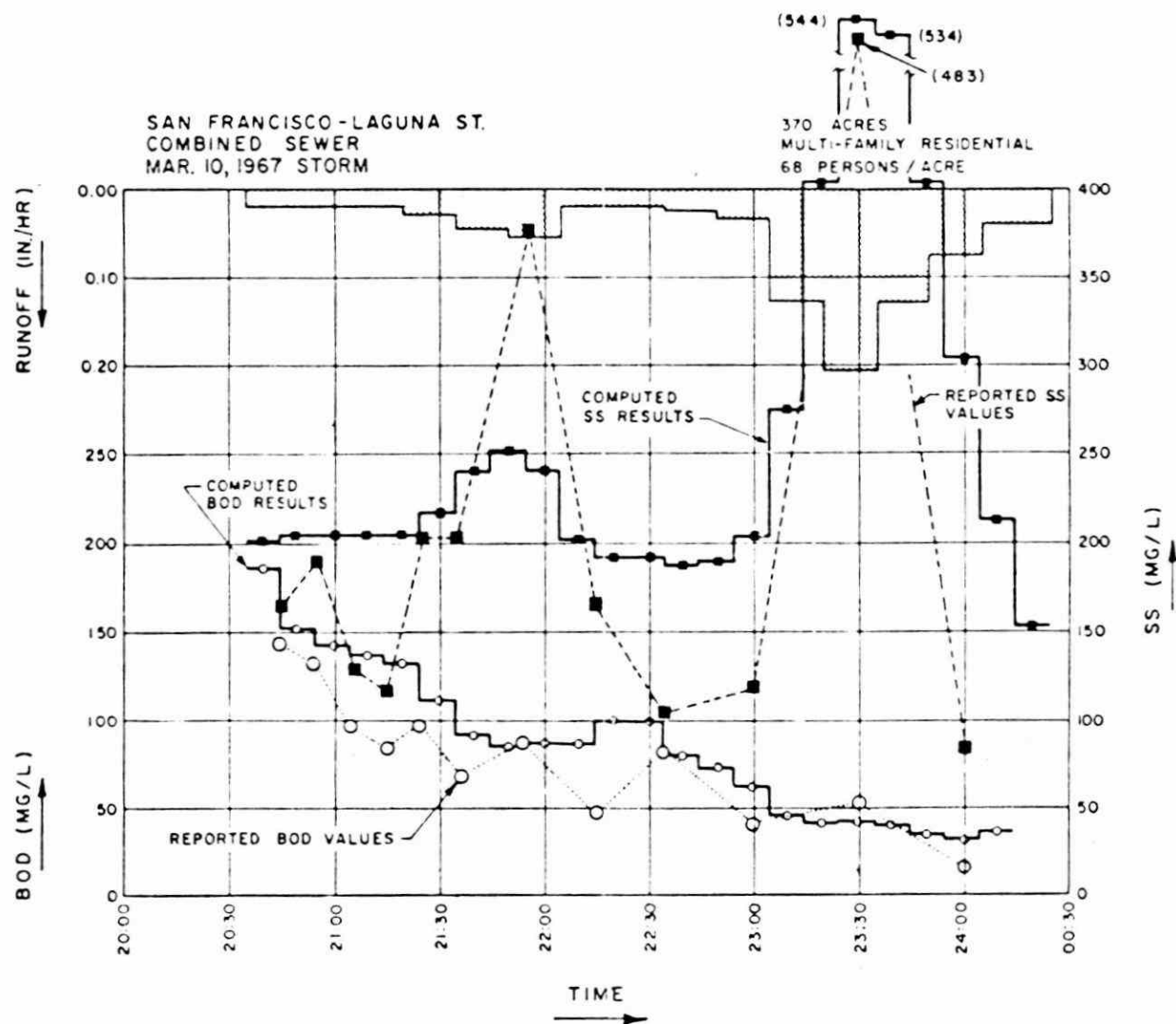
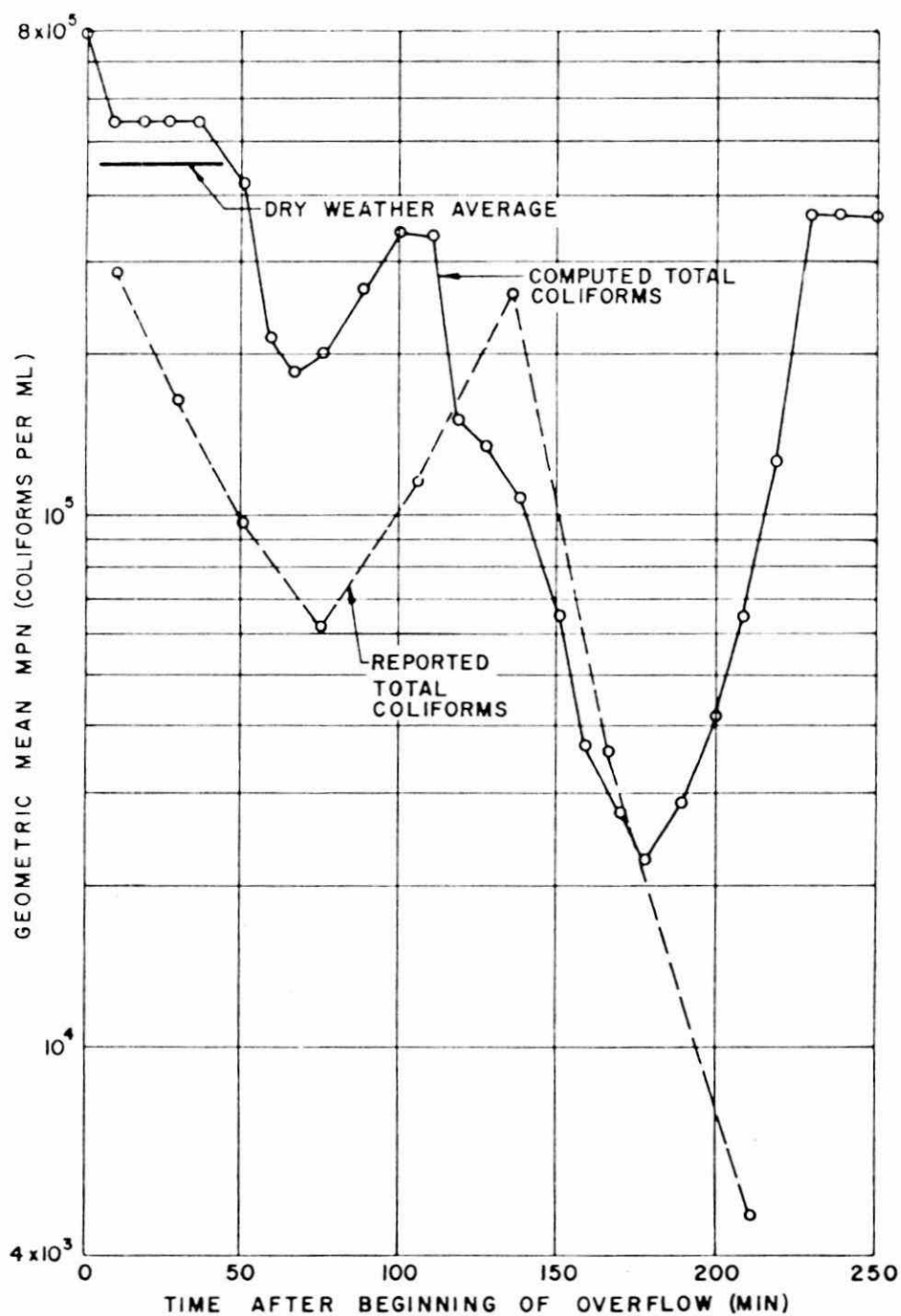


FIGURE 1. BOD AND SS TEST RESULTS FOR COMBINED SEWERS, LAGUNA STREET, SAN FRANCISCO [19]



San Francisco- Laguna St.
Combined Sewer March 10, 1967 Storm

FIGURE 2. TOTAL COLIFORM TEST RESULTS FOR COMBINED SEWERS [19]

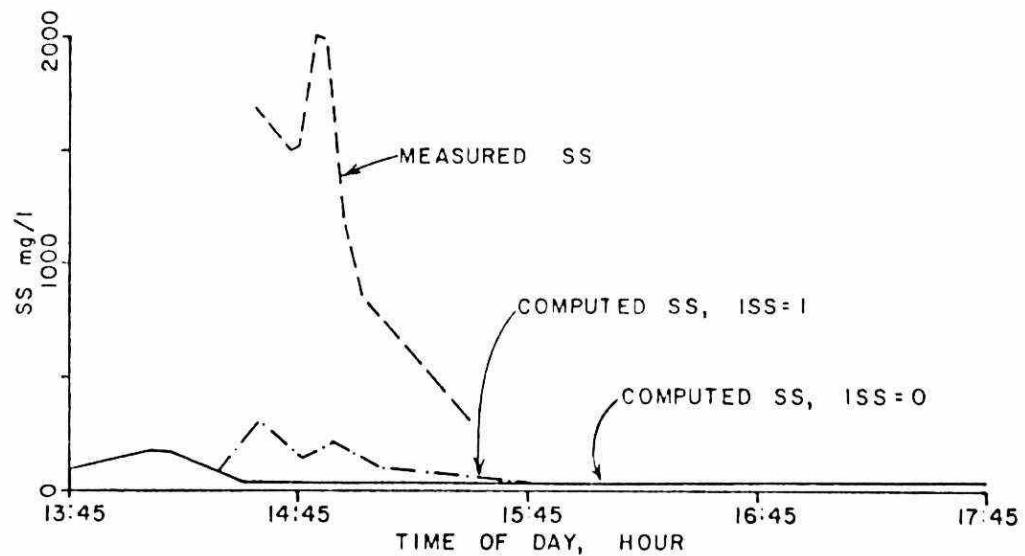
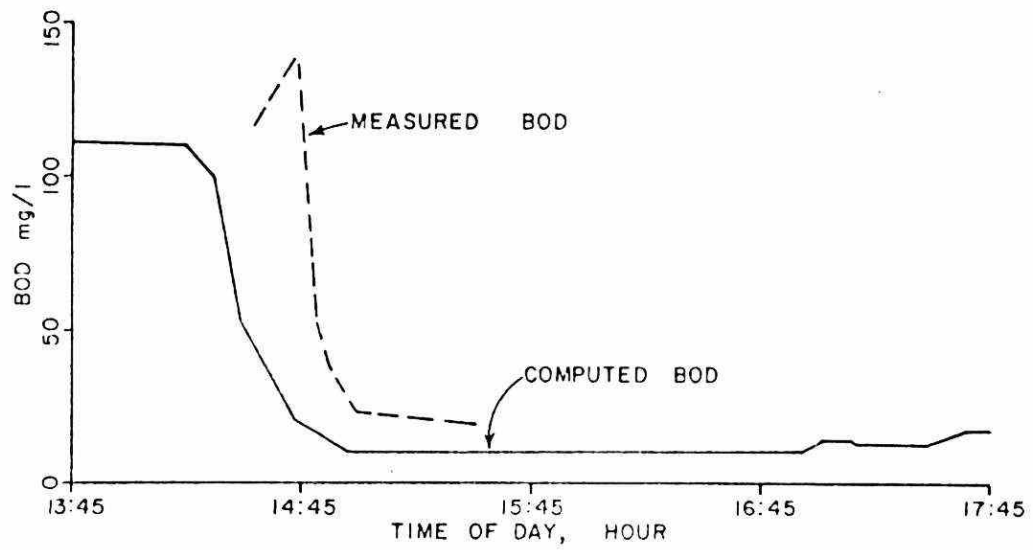
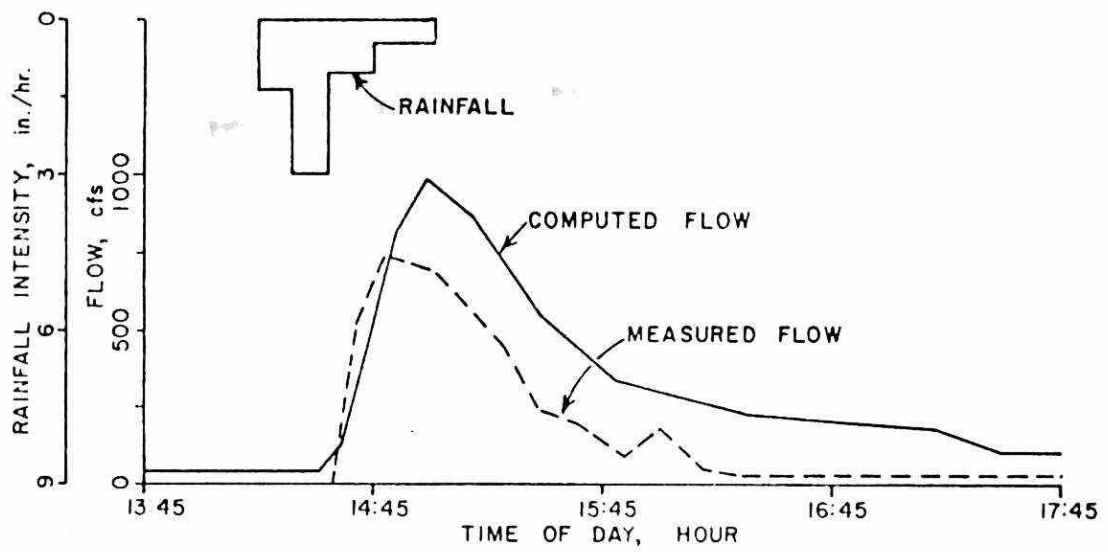


FIGURE 3. STORM EVENT OF JUNE 20, 1973 ATLANTA AIRPORT INPUT HYETOGRAPH [32]

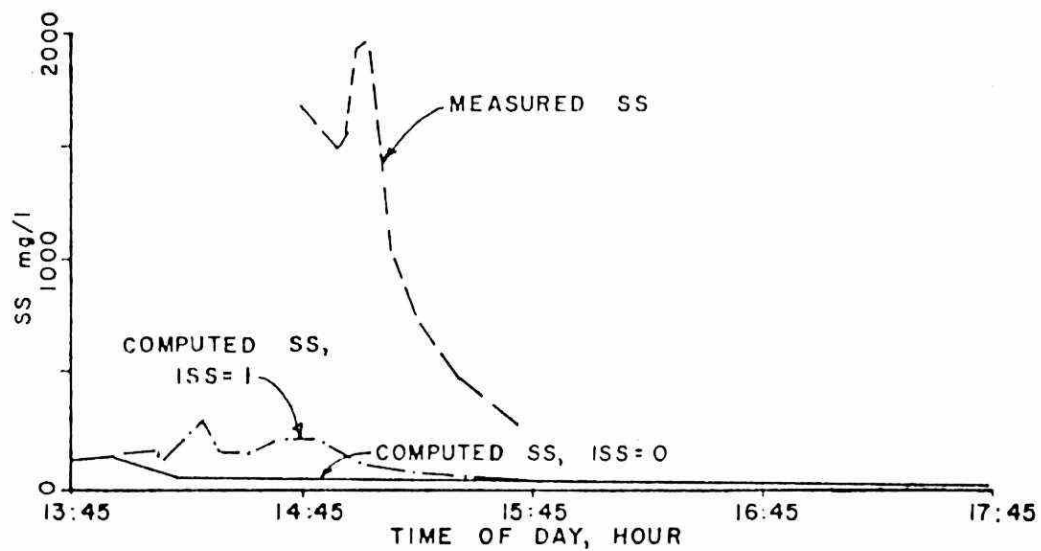
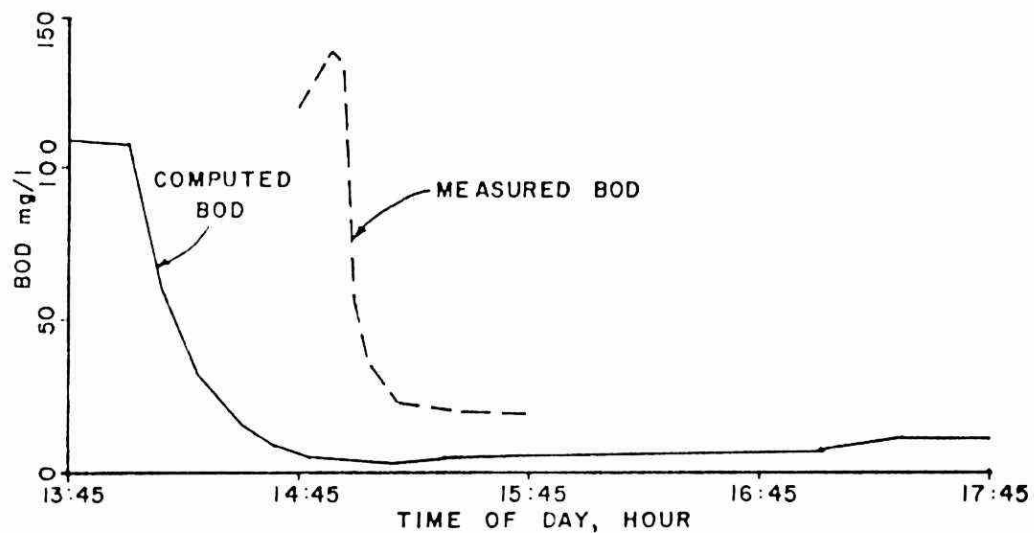
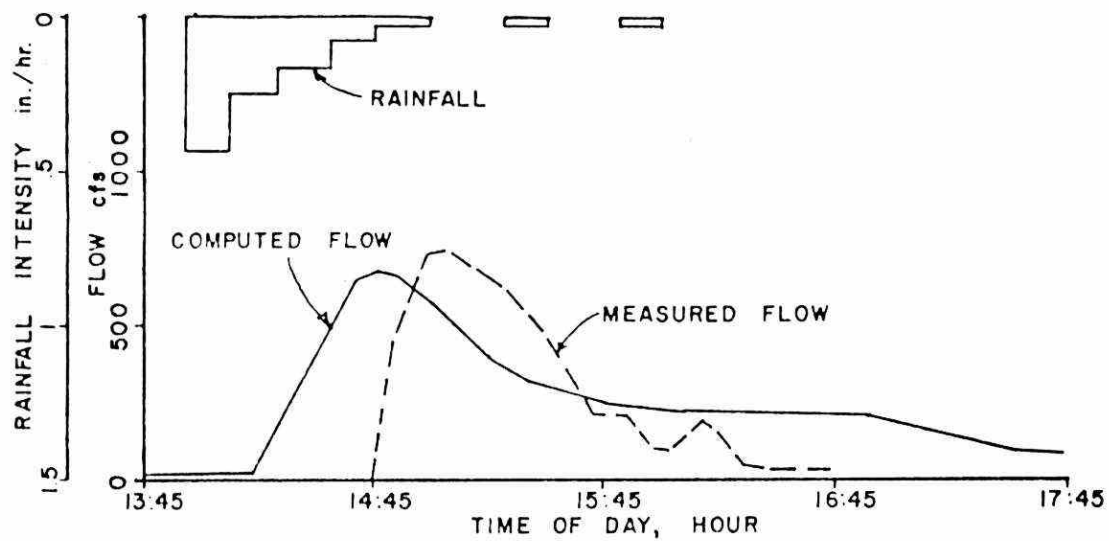


FIGURE 4. STORM EVENT OF JUNE 20, 1973 USGS STATION NO. 26
INPUT HYETOGRAPH [32]

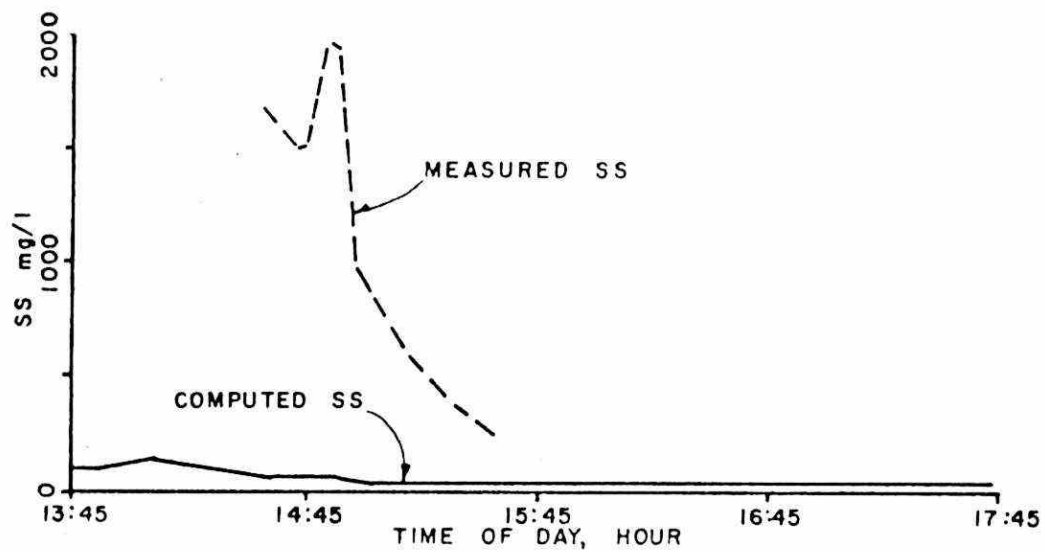
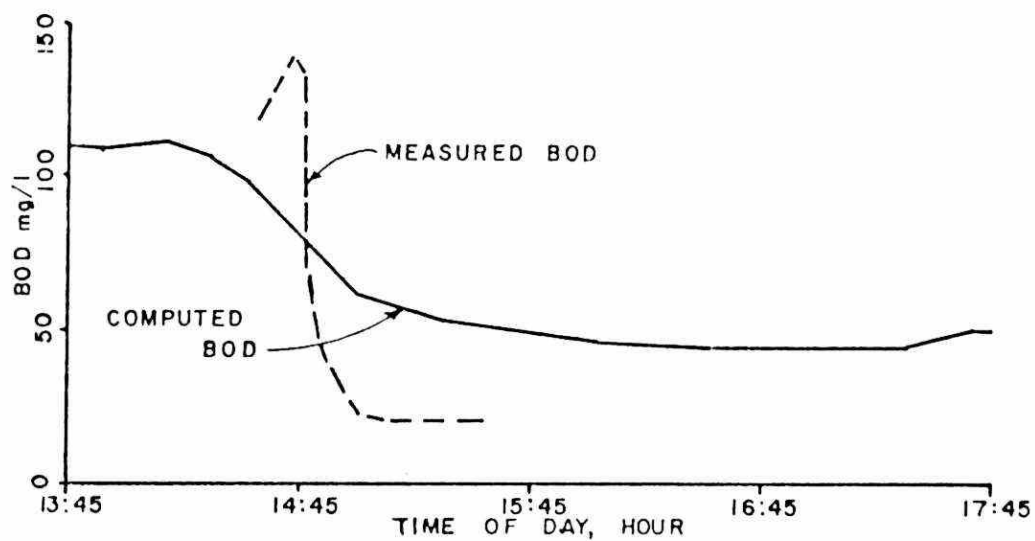
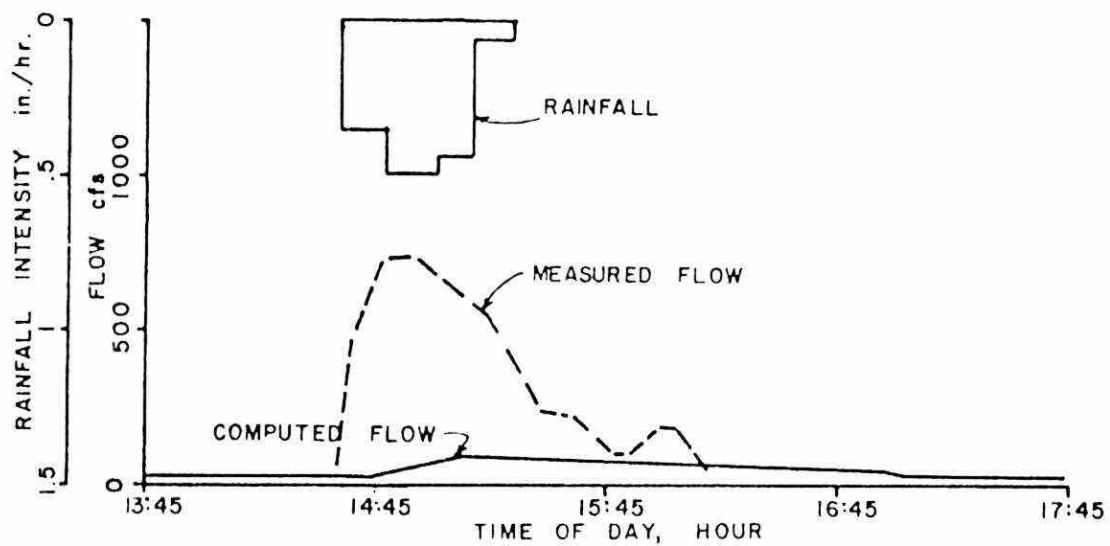


FIGURE 5. STORM EVENT OF JUNE 20, 1973 USGS STATION NO. 51 INPUT HYETOGRAPH. [32]

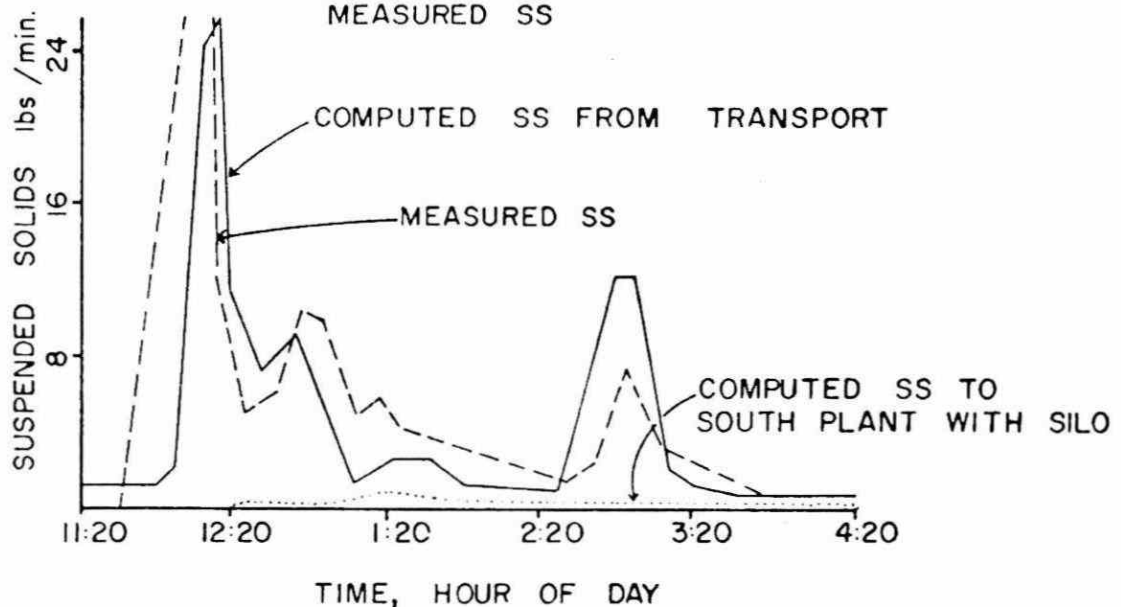
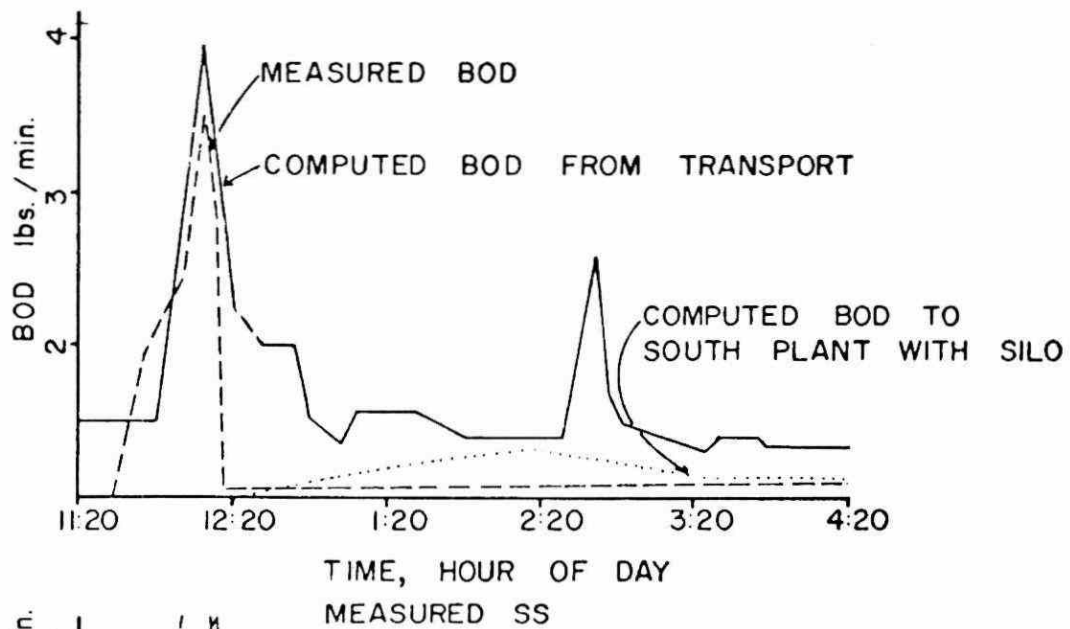
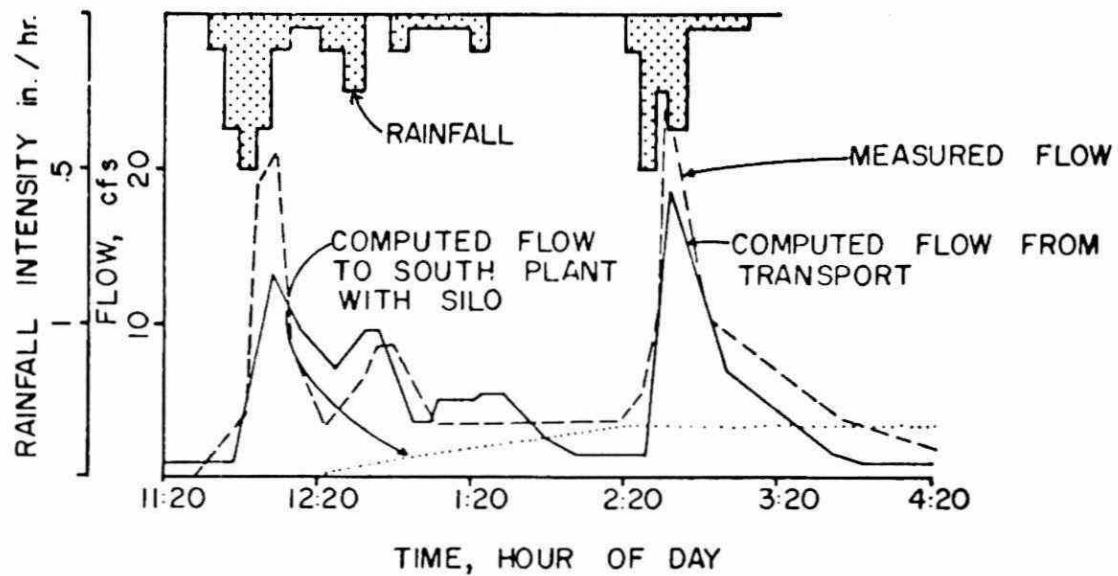


FIGURE 6. RUNOFF-TRANSPORT SIMULATION FOR STEVENS AVENUE WITH SILO AND SWIRL CONCENTRATOR, STUDY 3, NO OVERFLOW TO RIVER SINCE SILO CAPACITY NOT EXCEEDED [27]

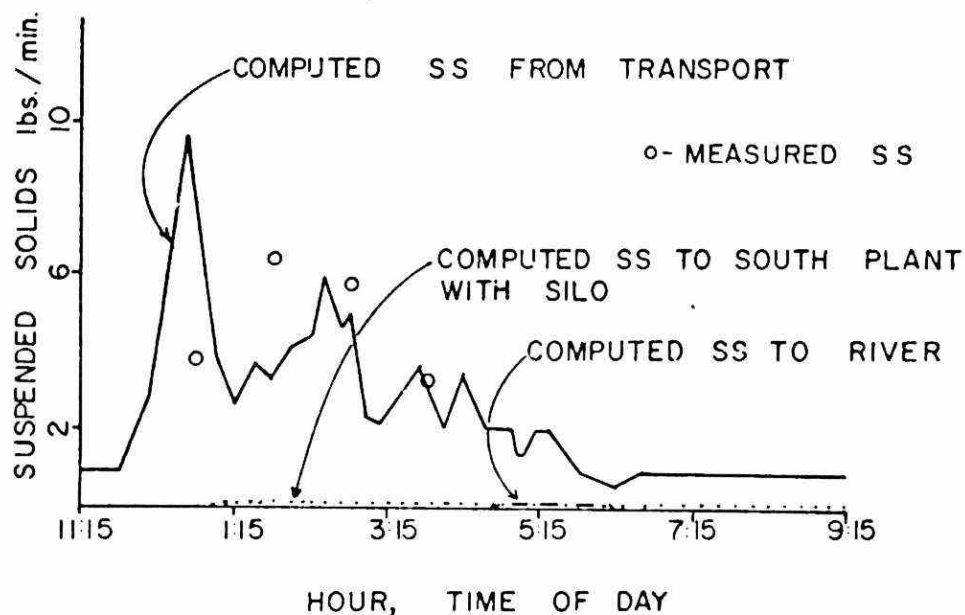
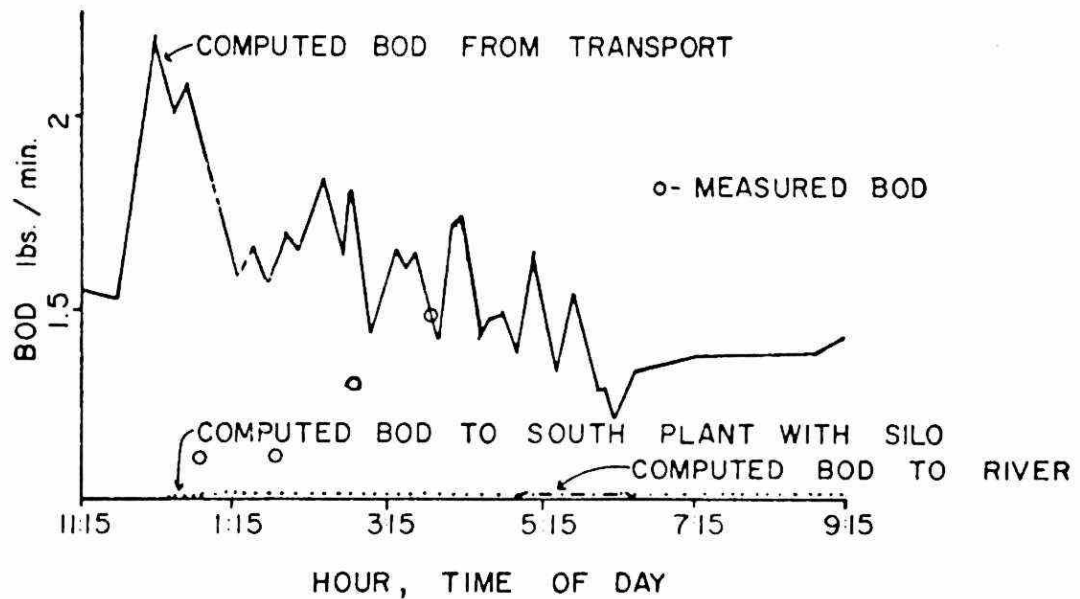
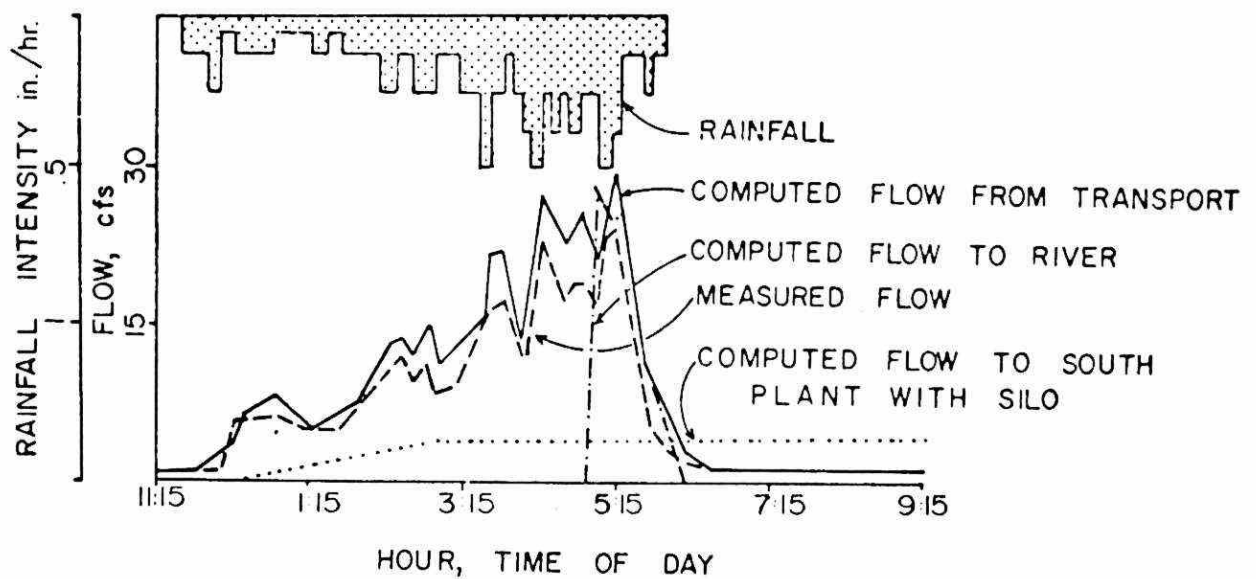


FIGURE 7. RUNOFF-TRANSPORT SIMULATION FOR STEVENS AVENUE WITH SILO AND SWIRL CONCENTRATOR, STUDY 4 [27]

(b) U.S. Army STORM - The STORM was calibrated against measurements from the Castro valley watershed, California [30]. The parameters selected for calibration were: 1) dust and dirt accumulation rates; 2) pollutant composition of dust and dirt; and, 3) the exponent, b , in the pollutant washoff equation. A comparison of calibrated values of pollutant loading rates, listed in Table 17 with default values shown in Table 18, reveals that the dust and dirt accumulation rates had to be increased by a factor of two, except for the open or park area which was increased by a factor of about six. Pollution composition of the dust and dirt was also increased by a factor of four for all parameters except suspended and settleable solids. Comparisons of computed and measured BOD concentrations are shown in Figure 8. Agreement in the first case was very good. However, computed values for the second storm were consistently low. No results are reported for the verification of the STORM.

Comparison of the SWMM and STORM models (see Table 19) reveals that many areas exist where these models are considerably different from each other, or where improvement is evidently required. For instance, both models need more calibration and verification, and the amount of pollutants removed by overflow structures could be considered in each model.

3.2.2 Statistical models

3.2.2.1 AVCO Corporation study. Relatively few studies have been reported in the literature concerning the estimation of pollutional characteristics of urban storm water runoff by applying a statistical approach. For such an extensive study conducted by AVCO Economic System Corporation [7], a large amount of data was collected (over 5,000 observations on 16 parameters) from 15 watersheds of different characteristics located in Tulsa, Oklahoma. The primary objective of the study was to develop functional relationships between various land use patterns and the amounts of various pollutants generally found in urban storm water runoff. The methodology used in investigating and formulating these relationships included the standard statistical techniques of correlation analysis, factor analysis, and multiple linear regression. The sets of input variables selected were: precipitation (current and antecedent

TABLE 17. CALIBRATED VALUES FOR POLLUTANT LOADING RATES FOR STORM
(CASTRO VALLEY, CALIFORNIA) [30]

Land Use	Dust and Dirt Accumulation lb/day/100 ft gutter	Pounds Pollutant per 100 lb of Dust and Dirt				
		Susp. Solids	Sett. Solids	BOD	N	PO ₄
Single Family	1.4	11.1	1.1	2.0	.19	.02
Multiple Family	4.6	8.0	.8	1.44	.24	.02
Commercial	6.6	17.0	1.7	3.08	.16	.03
Open or Park	9.2	11.1	1.1	2.0	.19	.02

Street Sweeping Efficiency = 70%

Washoff Exponent, b, = 2.0

TABLE 18. DEFAULT VALUES FOR POLLUTANT LOADING RATES IN STORM [10]

Land Use	Dust and Dirt Accumulation lb/day/100 ft Gutter	Pounds Pollutant per 100 lb of Dust and Dirt				
		Susp. Solids	Sett. Solids	BOD	N	PO ₄
Single Family	0.7	11.1	1.1	0.5	0.048	0.005
Multiple Family	2.3	8.0	0.8	0.36	0.061	0.005
Commercial	3.3	17.0	1.7	0.77	0.041	0.007
Industrial	4.6	6.7	0.7	0.3	0.043	0.003
Open or Park	1.5	11.1	1.1	0.5	0.048	0.005

Street Sweeping Efficiency = 70%

Washoff Exponent, b = 4.6

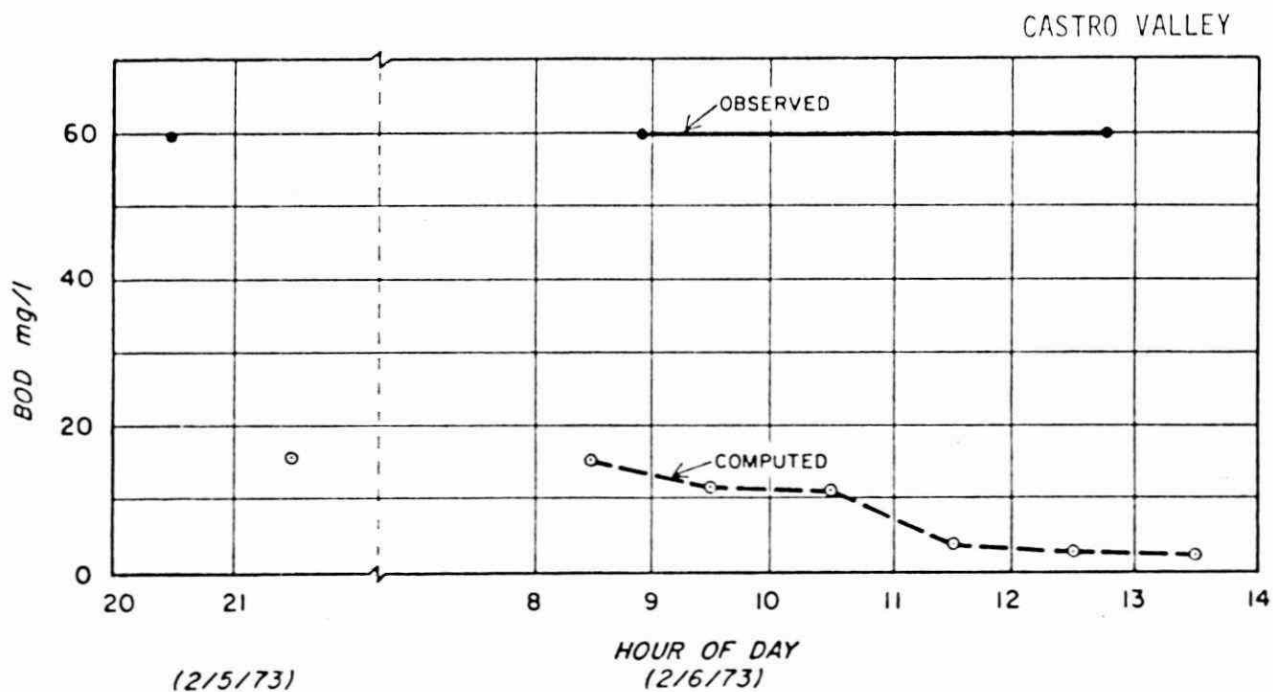
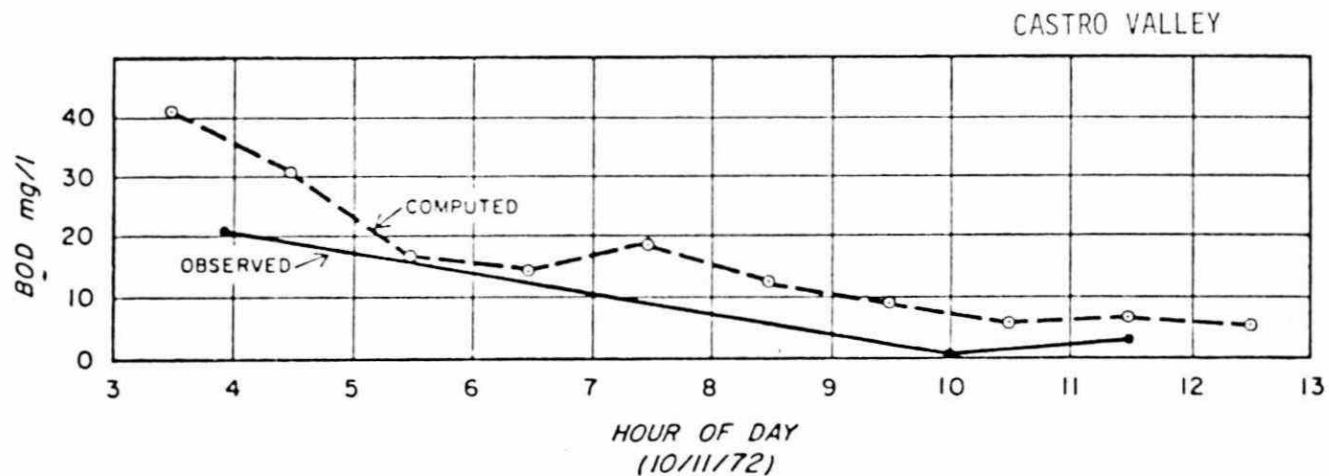


FIGURE 8. COMPARISON OF OBSERVED HOURLY VALUES OF BOD CONCENTRATION WITH VALUES COMPUTED BY STORM NOVEMBER 11, 1972 AND FEBRUARY 6, 1973 [30]

TABLE 19. COMPARISON OF SWMM AND STORM MODELS

	EPA Storm Water Management Model			U.S. Army STORM Model
	Old Runoff Model (ORM)	New Runoff Model (WRE)	New Runoff Model University of Florida	
Continuous Simulation	Single storm period, no water and quality bal- ance between storms	Same as ORM	Same as ORM	Continuous for several years
Time Interval	Selected in- terval in minutes	Same as ORM	Same as ORM	1 hour
Quality Con- stituents	Suspended Solids, BOD ₅ and coli- forms	Suspended and Settleable solids, BOD ₅ , COD, Coli- forms, Nitro- gen, Phosph- ate, and grease	Same as ORM	Suspended and Settleable solids BOD, Nitrogen, Phosphorus
Default Val- ues for dust and dirt accumulation rates	As per APWA study [17]	Lower default values for suspended and settleable solids as listed in Table 14. Same values for rest of the constituents	Same as ORM	Same as in SWMM with minor changes (See Table 17)
Values of Constant 'b'	4.6	4.6	4.6	4.6

TABLE 19. (CONT'D)

	EPA Storm Water Management Model				U.S. Army STORM Model
	Old Runoff Model (ORM)	New Runoff Model (WRE)	New Runoff Model University of Florida		
Method of Computation for quality constituents	Exponential equation for all parameters except susp. solids (eq. 2 & 3) uses eq. (7) for Suspended Solids	For all parameters uses eq. (2) & (3) with minor changes	Include two techniques for suspended solids on user's option; rest of the constituents are computed using eq. (2) & (3)	Uses equations (2) & (3); same method for all pollutants	
Availability factor, A	For susp. solids, eq. (5)	For all pollutants A=1	Eq. 5 for susp. solids and Eq. 6 for settle. solids	Uses eq. (5) & (6) for suspended and settle. solids, respectively	
Portion of Solids contributing to BOD	5% of Susp. solids	No	5% of susp. solids and 2% of Settleable solids	10% of Susp. solids and 2% of settleable solids	
Catchbasin Effect	Yes	Yes	Yes	No	
Dry weather flow quality	Yes	Yes	Yes	No	
Quality Routing in channels	Yes	Yes	Yes	No	
Quality reactions in channels	First-order decay without interactions for BOD	Same as ORM	Same as ORM	No	
Land surface erosion	Yes	Yes	Yes	Yes	

TABLE 19. (CONT'D)

	EPA Storm Water Management Model			
	Old Runoff Model (ORM)	New Runoff Model (WRE)	New Runoff Model University of Florida	U.S. Army STORM Model
Pollutant removed by overflow structures	No	No	No	No
Street cleaning practice considered	Yes	Yes	Yes	Yes
Vegetation Effect	No	No	No	No
Sedimentation and scour in channels	Suspended solids, considering particle size distribution	Same as ORM	Same as ORM	No

events); environment (general sanitary conditions); and, the geomorphological characteristics of the watershed (basin area, length of channel, relief and land slope). Accordingly, the output variables descriptive of pollution included the various bacterial, organic, nutrient, and solids parameter concentrations and their associated loadings. Consequently, simplified linear equations were established for prediction of water quality parameters, based on physical demographic and land use data. The agreement between computed and measured results was rather satisfactory in some cases, but poor in others.

Furthermore, these equations indicated that pollutant concentrations decreased with both the time since the start of the current precipitation event and the time since the antecedent event. Similarly, the bacterial and total solids concentrations increased with the average intensity of the current precipitation event. Also, the analysis of precipitation variables and BOD values taken during the rising limb of the hydrograph showed that the BOD concentrations decreased with increasing flow. The amounts of BOD contained in the flow increased with runoff rates because the time rate of flow increased at a greater rate than the BOD concentration decreased.

The functional relationships developed in this study between storm water pollution parameters and variables grouped in either the precipitation regimen or the land surface characteristics classification can be used to obtain first order estimates of the average pollutant concentrations in urban watersheds located in other cities.

However, a disadvantage of this model is that the model may not be equally applicable to other cities without extensive recalibration using large amounts of data. Moreover, the time variation of pollutant loading was not included in the final equations presented. Therefore, pollutographs showing pollutant concentration versus time cannot be obtained.

Nevertheless, these techniques provide an applicable procedure for looking at the impact of urban storm water pollutorial loads to the receiving streams and for planning storm water pollutorial control strategy for water quality management.

3.2.2.2 Sartor and Boyd study. Sartor and Boyd [11] also attempted to determine the relationship between the amount of contaminant material at a given site and the period of time which had elapsed since that site had been cleaned by either rainfall or sweeping. Various numerical analysis techniques were used to establish some type of correlation between time and the loading intensity. As a result, a number of equations were obtained relating to the elapsed time since the last cleaning (days) and the solids loading on the streets (lb/curb mile) for different land use classifications. Moreover, similar equations were also obtained for different particle sizes, etc. In general, it was found that industrial land use areas tended to accumulate contaminants faster than commercial or residential areas. The equations established in this study can be used to determine the first order estimate of solids loading intensity for a given watershed for which no such data are available. However, these equations can only give solids loading intensity (lb/curb mile) rather than amounts of individual pollutional parameters.

3.2.2.3 Battelle urban wastewater management model. Another comprehensive model, the Battelle Urban Wastewater Management Model [42], also uses regression analysis for computing storm water runoff quality. This model was developed primarily for the simulation of large urban catchments. It simulates the time-varying runoff and water quality in combined sewerage systems consisting of several catchments and a converging branch sewers network. This model can compute the quality of up to seven conservative pollutants. However, the model is limited to the simulation of single runoff events. Moreover, the model can be used for real time control of overflows during rainstorms and for least cost design of sewerage system modification. The model can be used in different modes, using various combinations of flow simulation, quality simulation, overflow control and design optimization. The model has been verified on very limited data.

3.2.3 Semi-empirical models

3.2.3.1 Arnett et al study. In a recent study by Arnett et al [8], a model, somewhat semi-empirical in nature, was derived from the data obtained from the 1962-63 Cincinnati study [12] as follows:

$$M(t) = K_1 + K_2 Q(t) + K_3 V(t)$$

where: $M(t) = C.Q.$ = mass flow of pollutant in storm runoff per unit area at time t , (pounds/hour/acre)

$Q(t)$ = storm runoff per unit area at time t , (cfs/acre)

$V(t) = \int_0^t Q(t) dt$ = cumulative volume of storm runoff per unit area since beginning of storm (cu ft/acre)

K_1, K_2, K_3 = constants.

The values of K_1, K_2 and K_3 were determined for different water quality parameters, including suspended solids, BOD, phosphate (PO_4) and nitrate (NO_3), and for different seasons, using regression techniques. Although not evident from the report, it appears that the model gave reasonable agreement with the measured values, despite its simplicity.

3.2.3.2 Graham et al study. Graham, et al [43], using regression analysis techniques, established different equations relating two different variables, watershed imperviousness and specific curb length (curb length/acre), to three independent variables: watershed households, population and employment densities. The following modified exponential function was used, in which the amount of growth of the dependent variable per increment of the independent variable declines by a constant percentage:

$$Y = k + ab^x$$

where: Y = dependent variable,
 x = independent variable,
 k = upper limit of dependent variable,
 b = ratio of successive differences of dependent variable (for $0 < b \leq 1$),
 $a = Y - k$ at $X = 0$.

Moreover, these equations can be used along with the storm water runoff block to estimate the effect of various land use schemes on runoff volumes and pollutant washoff loads.

Nevertheless, these relationships provide a valuable tool for estimating specific curb length and imperviousness because these data are generally not available for many watersheds.

3.3 Conclusions

Based on a detailed literature review, the following conclusions may be drawn:

1. Pollution of urban storm water may occur because of several sources of contaminants, which include street litter, gas combustion products, deicing salts and chemicals, rubber and metals lost from vehicles, decaying vegetation, domestic pet wastes, fallout from industrial and residential combustion products and chemicals applied to lawns and parks.
2. A substantial amount of data is reported on the quality of urban runoff. However, much of the data are presented in a form which is inappropriate for application to other areas. Additional problems of comparing data from various studies are variations in sampling methods, analytical procedures, and the fact that all studies do not measure comparable parameters. Furthermore, comparison of the results of various studies based solely on concentration units is difficult because of the flow-dependent, intermittent nature of the sources.
3. Wide variation has been found in the values of various pollutional parameters sampled at different locations, depending on a number of factors such as land characteristics of the catchment, intensity of vehicular traffic, antecedent dry period, street cleaning practices, frequency and efficiency of street sweeping, population density of catchment, and storm characteristics.
4. Much of the existing data reported in the literature are obtained from combined sewer systems, and this makes it difficult to determine the pollutional contribution of storm water runoff alone.
5. At present, adequate information regarding the potential pollutional contribution of urban storm water runoff does not exist for various

Canadian locations. Nevertheless, within recent years, several studies have been commenced to collect data on the characteristics and magnitudes of various pollutants on Canadian watersheds.

6. It is found that basically only one type of analytical model exists for urban runoff quality, as all current models are based on similar assumptions and use almost the same equations for estimating the amounts of different pollutants.
7. In the SWMM, two different methods for the computation of suspended solids are included which could be used on the user's option. Each method gives somewhat different results.
8. The main difference between the EPA's SWMM and the Corps of Engineers' STORM is that the SWMM is developed for detailed design purposes, while STORM is intended primarily for extensive planning applications. In the SWMM, runoff is limited to a single-event simulation while quality is simulated for a single catchment for several years. Moreover, the STORM is limited in its application to storm water drainage systems since it does not consider the quantity and quality of dry weather flow.
9. In both models, the SWMM and STORM, the accuracy of the water quality computations, particularly the formulation relating water quality with land use, has not been sufficiently established to be used with confidence for prediction purposes.
10. In both the SWMM and STORM models, some of the parameters which may be calibrated are: i) dust and dirt accumulation rates; ii) pollutant composition of dust and dirt; and, iii) the exponent, b , in the pollutant washoff equation.
11. Only a limited number of quality parameters were found to be simulated in all reported models, whereas sufficient information is now available for more parameters, such as chlorides, to be included.
12. Both in the SWMM and STORM, APWA study results have been programmed as default values. However, these results have been found to be considerably different from results obtained by others. Further,

the above default values can be modified according to the results from the Canadian studies.

13. More tests are needed to ascertain the value of the constant, b , in equation (2) and also the value of availability factor, A , in equations (5) and (6).
14. Statistical and semi-empirical models reviewed in the literature were found to be of limited application for practical purposes due to the large data requirements for calibration. However, the model presented by Arnett et al, predicted storm water runoff quality quite satisfactorily and, hence, this model can be applied to catchments for which flow quantity and quality measurements are readily available. Furthermore, equations developed by Graham et al can also be incorporated into the model for estimating specific curb length and imperviousness, if this information is not available for a particular watershed.

4. LITERATURE SURVEY - SNOWMELT QUANTITY

4.1 Snowmelt Factors

The general physical properties of snow and ice are well-known and have been documented by Mantis, Yosida, and others [65, 82]. Recent research into the physics of snow and ice has been summarized by Hirobumi [61]. Ven Te Chow [51] summarizes the international system of classification for newly fallen snow and gives its average density as one unit water equivalent for every ten units of snow depth.

Much of the current knowledge of the snowmelt phenomenon under natural conditions has been derived from detailed research in selected river basins by the U.S. Army Corps of Engineers (USCE). Considering snowmelt as essentially a heat transfer process, equation (1) has been widely used in recent studies of the snow melting process. This heat budget equation was first given by Wilson [81]. The heat available first raises the temperature of the snow pack to zero degrees Celsius and any additional heat causes snow to melt.

$$H_{\text{melt}} = H_{\text{snow}} - H_{\text{cc}}$$
$$H_{\text{snow}} = H_{\text{swr}} + H_{\text{lwr}} + H_{\text{ca}} + H_{\text{cond}} + H_{\text{g}} + H_{\text{p}} \quad (1)$$

where: H_{swr} = short wave radiation absorbed by the snow pack,
 H_{lwr} = net long wave radiation exchange with the snow-pack,
 H_{ca} = convective heat transfer from the air,
 H_{cond} = heat of vaporization released by condensate on the snow surface,
 H_{g} = heat conducted from the ground,
 H_{p} = heat content of precipitation,
 H_{snow} = change in heat storage of the snowpack,
 H_{melt} = heat available to melt a given amount of snow,
 H_{cc} = "cold content" of the snowpack.

The following paragraphs treat each of the heat budget components separately, in order to indicate their relative importance and to indicate how the USCE determines the components. The equations given were originally determined for rural snowmelt conditions.

The amount of heat required to produce 1 cm³ of water from pure ice at 0.0°C is defined as the latent heat of fusion of ice and is approximately 79.7 calories per gram.

Eagleson [54] defines the cold content of the snowpack by the following equation:

$$H_{cc} = -\int_0^{d_s} \rho_s C_s T_{sn} dz \quad \text{cal/cm}^2 \quad (2)$$

where: z = vertical coordinate, positive upward from ground surface, cm
and, assuming ρ_s , C_s and T_{sn} are independent of z , their average values are defined as:

$$\begin{aligned} \rho_s &= \text{density of snow, g cm}^{-3}, \\ C_s &= \text{specific heat of snow, cal g}^{-1} (\text{°C})^{-1} \\ &= 0.50 \text{ cal g}^{-1} (\text{°C})^{-1}, \\ T_{sn} &= \text{snow temperature, °C}, \\ d_s &= \text{snow depth, cm.} \end{aligned}$$

When the heat available is greater than the cold content, snow will melt. However, the amount of heat required to melt snow is different than the amount of heat required to melt an equal volume of ice. Therefore, it has been convenient to define Θ , the thermal quality of the snowpack, as the ratio of the heat required to obtain d_m inches of melt from snow, to the heat required to obtain d_m inches of melt from ice.

$$\begin{aligned} \Theta &= \frac{\rho_s d_s Lf_s + H_{cc}}{\rho_w d_m Lf} \\ &= \frac{Lf_s}{Lf} + \frac{C_s T_{sn}}{Lf} \end{aligned} \quad (3)$$

since by definition $\rho_w d_m = \rho_s d_s$

where: Lf_s = latent heat of fusion of snow,
 Lf = latent heat of fusion of ice.

According to the USCE [74], the short wave radiation component of equation (1) is most important in open or partly forested river basins. Other investigators have also indicated its importance, especially during the melt season, and also point out that slope and aspect of the river basin, as well as cloud cover and vegetation, affect the spatial distribution of solar radiation over the snowpack.

Solar radiation is generally defined as electromagnetic energy with wavelengths less than about four microns, while terrestrial radiation has wavelengths greater than four microns.

Most detailed physical snowmelt models use hourly or daily measured solar radiation values as input data. Monthly radiation summaries of the total downward direct and diffuse solar radiation quantities as received on a horizontal surface for each hour are published by the Atmospheric Environment Service of Canada [47]. According to Munn [66], solar radiation measurements are made to an accuracy of about 5%.

Across Canada, solar radiation is continuously measured at only about 40 meteorological stations.

Long wave radiation is generally estimated by use of the Stefan-Boltzmann law given by:

$$R = BT^4 \quad (4)$$

where: R = total long wave radiation

T = temperature ($^{\circ}\text{K}$)

B = $.826 \times 10^{-10}$ (cal. $\text{cm}^{-2} \text{min}^{-1} \text{ }^{\circ}\text{K}^{-4}$).

The snowpack is generally assumed to be a black body which emits radiation according to equation (4), when the temperature is assumed to be the temperature of the surface of the snowpack. The USCE [75] gives empirical methods by which the back radiation from clouds and forests can be estimated. For cloudy skies, and excluding effects of forests, the following equation is given:

$$R_{\text{cloudy}} = (EBT_a^4 - BT_{\text{sn}}^4) (1 - kN) \quad (5)$$

where: E = atmospheric emissivity,
 k = factor depending on type and height of clouds,
 N = decimal fraction of cloud cover,
 T_a = air temperature,
 T_{sn} = snow temperature.

Assuming that, for a forested area, the trees have the same temperature as the air and that 100% canopy closure will act as a black body, the following equation is used to estimate long wave radiation:

$$R_{\text{forest}} = B (T_a^4 - T_{sn}^4) \quad (6)$$

Equations (5) and (6) are combined into the following equation for a partly forested area:

$$H_{\text{lwr}} = FC B (T_a^4 - T_{sn}^4) + (1 - FC) (E B T_a^4 - B T_{sn}^4) (1 - kN) \quad (7)$$

where: FC = area average forest cover as a decimal fraction.

Equation (7) gives only a rough approximation of the net long wave radiation but has been used in several studies where detailed data required for other methods are not available. Hendrick and others [60] have recently attempted to more accurately define the effect of forest cover on snowmelt with respect to such factors as forest type and canopy transmission of solar radiation. Nothing concerning long wave radiation in the urban environment has been found in the literature.

The convection and condensation heat components are generally determined by the theory of turbulent exchange. The USCE has derived a generalized turbulent exchange equation assuming a power-law distribution for the particular property. The modern derivation is given by Eagleson [54].

$$Q = (k'/n) (Z_a - Z_b)^{-1/n} q_a v_b \quad (8)$$

where: Q = time rate of flow of the property,
 q_a = property gradient,

k' = constant of proportionality,
 V_b = wind velocity at elevation b ,
 n = exponent of the power law distribution,
 Z = height of measurement at levels a and b .

According to Viessman [77], USCE [74] and others, the power law distribution

$$\frac{q_2}{q_1} = \left(\frac{Z_2}{Z_1} \right)^{\frac{1}{n}} \quad (9)$$

characterizes a stable atmosphere, while a logarithmic profile is used to represent neutral conditions.

When estimating the heat of condensation (H_{cond}), the property of interest is water vapour transport, which can be expressed in terms of the specific humidity. This is given in terms of vapour and air pressure as:

$$q = 0.622 \, e / P_a \quad (10)$$

where: e = vapour pressure of moist air (mb),
 P_a = total pressure of moist air (mb).

Substitution of the specific humidity gradient into the general turbulent exchange equation results in the following expression for mass of moisture transfer per unit time:

$$M = (k' / n) (Z_a Z_b)^{-1/n} (.622 / P_o) (e_a - e_s) V_b \quad (11)$$

where: e_a = vapour pressure at level,
 e_s = vapour pressure above the snow,
 k' = constant of proportionality related to air density and elevation,
 P_o = sea level pressure.

For every gram of water which condenses, 600 calories of heat are released. Therefore,

$$H_{\text{cond}} = 600 (k' / n) (Z_a Z_b)^{-1/n} (.622 / P_o) (e_a - e_s) V_b \quad (12)$$

A similar expression has been derived for the heat of convection:

$$H_{ca} = (k'/n) (Z_a Z_b)^{-1/n} c_p (T_a - T_{sn}) V_b \quad (13)$$

where: T_a = air temperature at level Z_a ,

T_{sn} = temperature of the snow surface,

c_p = specific heat of air.

The above relationships were originally developed for application to rural watersheds.

Rain falling on a snowpack is cooled to the temperature of the snow, thus giving up an amount of heat H_p equal to one calorie per gram of rain water for every degree Celsius change in temperature. Therefore, the following equation has been widely used to estimate H_p :

$$H_p = (T_r - T_{sn}) P_r \quad (14)$$

where: T_r = rain temperature ($^{\circ}\text{C}$),

P_r = rainfall depth (cm).

Since the precipitation temperature is usually close to the snow temperature, H_p is generally small.

Heat conduction from the ground (H_g) can be represented by the following simple differential equation:

$$H_g = K' \frac{dT}{dZ} \quad (15)$$

where: K' = thermal conductivity of the soil,

$\frac{dT}{dZ}$ = temperature gradient of the soil.

According to Viessman [77], Eagleson [54], Chow [51] and others, the heat conduction from the ground is generally negligible on a daily basis. Eagleson gives a daily value in the order of magnitude of $10^{-3} \text{ cal cm}^{-2}$. Gray [56, 57] postulates that soil heat tends to offset the negative

long wave flux from the snowpack at night rather than contribute significantly to melting.

However, according to Santefort et al [72] based on the results of studies conducted in the Lake Superior region, midwinter ground thaw is an important hydrologic factor which not only may supply a significant ground heat reservoir, but also increase snowmelt percolation to the groundwater flow.

4.2 Modelling of Snow Accumulation and Melt

4.2.1 General

Many recent computerized snowmelt models are based on variations of the theoretical considerations summarized in the previous section and thus require considerable data input. For example, the snowmelt runoff model developed by Anderson [46] requires measured temperature, wind speed, solar radiation, precipitation, and vapour pressure of the air as input data. A comprehensive snowmelt model developed by Amorocho and Espildora [44] requires, in addition to these parameters, the measured dew point and wet bulb temperatures and cloud cover amount and type, on an hourly basis. Few attempts at adapting these complex models to Canadian conditions have been reported in the literature, presumably because of their exacting data requirements. These models are discussed in more detail in the following sections.

Recently, attempts have been made to define the most important snowmelt parameters. For example results of measurements taken by Jolly [62] on a partly urbanized watershed near Ottawa have shown that air temperature and radiation can explain most of the snowmelt runoff for rainfree days. Air temperature alone also gave a high correlation for predicting snowmelt. Gray [56] has shown that, on the prairies, net radiation is the dominant energy source for snowmelt at the beginning of the melt and that the amount of sensible heat transfer progressively increases in importance as bare ground appears.

4.2.2 Basin snowmelt equations

Several empirical basin snowmelt equations based on the theoretical equations given above have been developed by the USCE and have

been used where geographical and meteorological conditions are similar to those in the western United States, where the equations were developed. Most recently, these basin snowmelt equations have been incorporated into a mathematical river basin model developed by the USCE [75].

For practical applications, the USCE developed (using several assumptions) generalized empirical forms of the heat budget equations given above. Gray [55] summarized the generalized forms in the following manner in terms of inches per day of snowmelt from a ripe snowpack:

A. During Rain

- (i) For open and partly forested regions (0-60% cover)

$$M = (0.029 + 0.0084 k v_b + 0.007P) (T_a - 32) + 0.09 \quad (16)$$

- (ii) For heavily forested regions (60-100% cover)

$$M = (0.074 + 0.007P) (T_a - 32) + 0.05 \quad (17)$$

where T_a is the air temperature ($^{\circ}\text{F}$) at the 10' height.

B. During Rain-free Periods

- (i) Open areas (<10% cover)

$$M = k' (0.00508 R_{si}) (1-A) + (1-N) (0.0212 T_a' - 0.84) + N(0.029 T_c') + k(0.0084 v_b) (0.22 T_a' + 0.78 T_d') \quad (18)$$

- (ii) Partly forested areas (10-60% cover)

$$M = k' (1-F) (0.004 R_{si}) (1-A) + K(0.0084 v_b) (0.22 T_a' + 0.78 T_d') + F(0.029 T_a') \quad (19)$$

- (iii) Forested area (60-80% cover)

$$M = K(0.0084 v_b) (0.22 T_a' + 0.78 T_d') + 0.029 T_a' \quad (20)$$

- (iv) Heavily forested areas (>80% cover)

$$M = 0.074 (0.53 T_a' + 0.47 T_d') \quad (21)$$

where: M = snowmelt rate (in/day),

T_a' = difference between air temperature at 10' ht. and the snow surface temp. ($^{\circ}\text{F}$),

T_c' = difference between the cloud base temp. and the snow surface temp. ($^{\circ}\text{F}$),

- T_d' = difference between dewpoint temperature at 10 ft height and the snow surface temperature ($^{\circ}\text{F}$),
 V_b = wind speed 50 ft above the snow surface (mph),
 R_{si} = observed or estimated solar radiation on a horizontal surface (Langleys),
 A = snow surface albedo,
 k' = basin shortwave radiation melt factor,
 K = basin condensation-convection melt factor,
 F = estimated basin forest cover,
 N = estimated cloud cover.

Many other simplified models use only readily available information, assuming certain components in the heat budget equation can be neglected in the specific case. For example, Willen, et al [80] have recently used the following snowmelt function based only on the long and short wave radiation components:

$$H_{\text{snow}} = R_g (1-A) + FC (BT_a^4 - BT_{\text{sn}}^4) + (1-FC) (EB T_a^4 - BT_{\text{sn}}^4) \quad (22)$$

where: A = snow albedo,

R_g = global solar radiation.

In using equation (22), it was assumed that the effect of cloud cover was indexed by the measured solar radiation values.

4.2.3 Degree-day method

Temperature index methods such as the degree-day method are generally in widespread use because of the relatively simple computation and limited data requirements. A degree-day is defined as a deviation of one degree from a given datum temperature over a 24-hour period.

Snowmelt is, therefore, given by the following simple equation:

$$\text{MELT} = C (T_a - T_{\text{sn}}) \quad (23)$$

where: C = coefficient determined by trial for the particular basin,

MELT = snowmelt in centimeters or inches per day,

T_{sn} = base temperature for melt,

T_a = air temperature.

For some applications, degree-hour computations can be made. This simple equation is used in the existing urban STORM runoff model [76]. Other variations on this simple equation are common, for example Pysklywec [68] incorporates degree-day factors and meteorological parameters into a regression equation developed for a specific basin. Pysklywec's regression equation had the following form:

$$M = 0.615 + 0.0373n + 0.00607R_L + 0.00201 (T-36)V + 0.0437 (RH)V + 0.0007P (T-32) \quad (24)$$

where: M = snowmelt (in/day),
 n = sunshine (hr/day),
 R_L = long wave radiation (langley/day),
 T = temperature ($^{\circ}\text{F}$),
 V = wind velocity (mph),
 RH = relative humidity,
 P = rainfall (in/day).

Solomon and Quershi [73] extended the degree-day method by incorporating it into a parametric river basin model which is capable of estimating snow accumulation and runoff at the end of each month. Models of this kind use optimum basin parameters determined by an iterative procedure (e.g. Rosenbrock [71]) which minimizes an objective function of the following form:

$$F = \sum_{i=1}^M (R_c - R_m)^2 \quad (25)$$

where: R_c = computed runoff per unit time,
 R_m = measured runoff per unit time.

The coefficient C is thus determined from the optimization process.

The degree-day method generally gives satisfactory results in view of the assumptions and data limitations. For example, Anderson [45] compared a more detailed heat budget method with a degree-day method, and concluded that both methods gave quite similar results. However, it must be pointed out that the degree-day methods cannot accurately account for depth or density of snow on the ground.

4.2.4 Amorocho's model

This model is an attempt to deterministically describe the snow accumulation and melt phenomena. The model estimates components of the heat budget equation by using the generalized relations developed by the USCE. The model assumes that the snowpack can be divided into three layers, with heat exchange with the environment taking place only in the upper layer. No heat or water vapour transfer is assumed to take place between the layers other than heat carried by the percolating water.

It is a continuous simulation model which was developed for use in a detailed hydrologic river basin model. After each new snowfall or melt the snowpack parameters are geometrically weighted by simple proportion according to depth changes in each layer. The main effect of using a layered model is the ability to obtain a built-in lag time to runoff of melt from the upper layer, according to the water holding capacities of the lower layers.

The following list of meteorological report variables is required by the model:

- short wave radiations ($\text{cal}/\text{cm}^2/\text{hour}$);
- air temperature ($^{\circ}\text{F}$);
- dew point temperature ($^{\circ}\text{F}$);
- wind velocity (mph); and,
- cloud cover (tenths of sky).

Output from the model includes the density, depth and water equivalent of snow, as well as the amount of excess water reaching the ground which is available for runoff. Computations take place on an hourly basis.

At the University of Waterloo, Amorocho's snowmelt model has been reprogrammed into subroutine form. The model is used in conjunction with meteorological models and a physiographic data bank in order to simulate distributed snow accumulation and melt using generally available daily data [48].

The Waterloo model was developed specifically for Canadian conditions where the major problem is usually the lack of suitable input data. In this regard, independent meteorological models for estimating solar radiation and wind speed were interfaced with the snow model. Spatial distribution is accounted for by using the square grid technique. The meteorological models are used where measurements of wind and solar radiation are not available.

4.2.5 Stanford and Hydrocomp snowmelt models

The Stanford Watershed Model IV uses a snowmelt subroutine developed especially for basins with sparse data. Only temperature data are used, although estimates or some calibration of melt parameters are required. The option of inputting measured short wave radiation data to improve the snowmelt estimates also exists [53].

Another model patterned after the Stanford Watershed Model IV is the Hydrocomp Simulation Program (HSP) [29]. A heat budget approach is used which requires estimates or calibration of some parameters. The model requires eleven parameters for snowmelt, of which eight must be calibrated or estimated. Data requirements include mean daily cloud cover, incoming short wave radiation, wind velocity, temperature and dew point temperature. The method of calculating overland flow from snowmelt is not well documented, but probably uses the same equations as for rainfall runoff.

In a survey of available hydrologic models by Linsley, it was concluded that "Of the existing models, the various versions of the Stanford Watershed Model appear to most nearly satisfy the need for urban storm runoff models, with the HSP apparently most closely meeting the desired specifications". (This was before publication of the EPA-SWMM and no special attention was given to the merits of the snowmelt simulation procedures.)

4.2.6 U.S. National Weather Service snow accumulation and ablation model

Anderson [46] developed a relatively simple snow accumulation and ablation model for use with the U.S. National Weather Service River Forecast System. By making several assumptions, most of the physical

parameters accounting for snow accumulation, melt, areal distribution and time lag to runoff were included in the model.

For periods of no rain or light rain, the degree-day melt equation (23) is used to compute snowmelt. Melt during periods of significant rain is given by the following equation:

$$\begin{aligned} \text{Melt} = & (T_a - 32) (0.007 P_x + 7.5 \gamma F(u) + 0.00117 \Delta T) \\ & + 8.5 F(u) (e_a - 0.18) \end{aligned} \quad (26)$$

where: T_a = air temperature ($^{\circ}\text{F}$),

$F(u)$ = wind function = $.006 V \Delta T$,

e_a = vapour pressure of the air (inches Hg),

P_x = rainfall (inches/hour),

γ = psychometric constant

= $.000359 P_A$ where P_A = air pressure (inches/Hg)

ΔT = time interval in hours,

V = wind speed (mph).

The terms in this equation were derived from the generalized heat budget equations developed by the USCE by making the following assumptions:

- 1) Incoming solar radiation is zero during rain.
- 2) Incoming long wave radiation equals the black-body radiation at the ambient air temperature.
- 3) The snow surface temperature is 32°F .
- 4) The dew point temperature is equal to the ambient air temperature.
- 5) Temperature of the rain water is equal to the ambient air temperature.

The model also allows for negative heat storage in the snowpack and accounts for lag of melt and precipitation by using empirical relationships.

The main advantage of this model is that it requires only temperature as an input parameter. Vapour pressure and air pressure can be input or computed by approximate physical relationships.

The wind function can be variable or a constant average value can be assumed, depending on the situation and data available. The areal depletion of snow cover is assumed to be a function of snow water equivalent.

The model has been tested and gives good results in conjunction with the National Weather Service River Forecast System flow simulation model.

4.2.7 Other models

Various other models of the snow accumulation and melt processes have been described in the literature. For example, Provart [67] developed a model which uses measurements of air temperature, relative humidity, wind speed, precipitation and net radiation. The model has been tested by Whiteley et al using measurements obtained from the Blue Springs Creek I.H.D. Basin near Guelph [78, 79]. According to Whitely (personal communication) there are no corresponding measurements available for watersheds with a high degree of urbanization.

Mr. B. Goodison of the Atmospheric Environment Service (AES), Environment Canada, is currently developing a snow accumulation and ablation model. Eventually, he intends to assess the applicability to Canadian conditions of the coefficients generally used in the USCE heat budget equations. Goodison is operating an index plot near a snow course location north of Toronto. However, the measurements which have been taken to date are not yet in useable form. In any case, such data would be of limited use in calibration a snowmelt model for highly urbanized catchments.

At the Ontario Ministry of the Environment a lumped snowmelt model is being developed by Mr. L. Logan (personal communication). The physical melt equation is based on the work of the U.S. Corps of Engineers. The model forms part of a comprehensive watershed model designed essentially for rural catchments.

Most of the previously mentioned models rely on the digital computer. However, Riley et al [69, 70] recently developed an analogue model using several simple differential equations to predict average changes

in snowpack parameters such as density, water holding capacity, albedo and temperature. A modified form of the degree-day equation was then used for snow melt with some limited success.

4.3 Snowmelt Infiltration and Runoff Factors

Most of the snowmelt models previously discussed have been developed for use with hydrologic river basin models at various levels of sophistication. However, according to Langham [64] the modelling of the rate at which snowmelt water appears in the receiving water body is usually similar to that for rain falling on bare ground. That is, in many models, the delay in the passage of the melt water through the snowpack is not accounted for in describing the relationships between snowmelt and runoff. Anderson [46] accounted for the lag and attenuation of excess liquid water moving through a snowpack as a function of the water equivalent of the pack by using an empirical relationship.

Theoretical relationships have been proposed by Colbec [52] to describe the processes of water movement through snow by assuming it to be a porous medium. However, Langham [64] pointed out that a snowpack is rarely entirely porous and, in many cases, contains frozen ice layers and lenses which may be more important than the microstructure in controlling the flow of melt water. This aspect is particularly important in geographical areas where the snowpack is continuously subjected to thawing and refreezing. According to Langham, in some cases the presence of ice layers may result in more free water detention above each layer and, thus, results in a slower response time to runoff. The problem is obviously complex and not enough data have been collected to date to construct a practical detailed model of the phenomena.

Another aspect of the modelling problem is the difficulty in accounting for the melt water infiltration to the ground. It has long been recognized that relatively deep snowpacks which accumulate early in the winter season may act to insulate the ground, which then remains unfrozen. On the other hand, in areas with thin or variable snow cover, the ground may be frozen or partially frozen. Depending on the initial water content, the permeability of the frozen ground can range from essentially impermeable to permeable [50]. In fact, Bloomsburg [49]

stated "if soil is frozen it is possible to have a greater permeability than in the unfrozen state".

Klock [63] pointed out that the problem is further complicated by the fact that the hydraulic conductivity of the soil decreases with the temperature of the infiltrating water, as well as varying with the physical properties of the soil. Therefore, snowmelt water near the freezing point increases the possibility of having a greater overland flow.

Theoretical relationships describing the phenomena of water movement through porous media have been proposed by Harlan [58] who stated that "Any realistic simulation model, for example of the snowmelt infiltration process, must consider the effects of past events as well as current conditions on the response of the system". Harlan [59] also described the processes of ground conditioning and the response of the groundwater table under winter conditions. However, few quantitative measurements of the physical, hydraulic or thermal properties of frozen and partially frozen soils have been made or reported in the hydrologic literature.

Anderson [46] also recommended further research on the movement of meltwater and rain through a snowpack, and the effect of frozen ground and slush layers on the amount and timing of runoff.

Such measurements would be required to substantiate or calibrate any realistic model of the snowmelt infiltration processes.

4.4 Conclusions and Recommendations

It is apparent that the current state-of-the-art of snowmelt modelling allows for a minimum time step computation for snowmelt of one hour. Indeed, most existing models perform computations at 6 or 24 hour intervals. Furthermore, most of the sophisticated models require a large amount of meteorological data as input. Also, the more accurate models generally require calibration of several parameters. However, for application to most urban conditions the large amounts of input data required may not be the most important limiting factor, since first-order meteorological stations are usually present in urban centres. That is, in many cases, the meteorological data required could be obtained from the data bank maintained by the Atmospheric Environment Service.

A more important consideration with respect to snowmelt modelling is the computational accuracy required. As demonstrated by Anderson and others, the degree-day method can provide reasonable estimates of snowmelt when compared to the more detailed heat budget models. During nonrain periods the degree-day method will give accurate estimates of the total volume of runoff, provided the amount of snow on the ground is accurately known.

However, a more accurate estimate of snowmelt is required during rain or snow events. This can be provided by making certain assumptions and using the generalized heat budget equations. In view of these conclusions, the snowmelt model developed by Anderson is recommended for integration with the EPA's SWMM.

Anderson's snowmelt model can be considered to supply the required degree of accuracy in view of the lumped nature of the SWMM model. That is, it is anticipated that urban areas can be described by the following input data, which assume that the physical characteristics associated with the melt runoff phenomena in each subcatchment can be lumped:

- 1) bare impervious area of the subcatchment;
- 2) snow covered impervious areas of the subcatchment and water equivalent of snow cover;
- 3) bare pervious area of the subcatchment;
- 4) snow covered pervious area of the subcatchment and water equivalent of snow cover; and,
- 5) the associated surface roughness and depression storage for each area. (For snow covered areas the surface storage is a function of the snow water equivalent.)

For urban areas during rain on snow events, it is anticipated that rainfall could contribute significantly more than snowmelt to the runoff hydrograph. This is due partly to the fact that part of the impervious urban area may be bare (e.g. streets and roofs) and partly because rainfall intensity is usually significantly greater than snowmelt intensities.

The main influence of snow on the ground will be to increase the surface depression storage parameter. Snow will hold an amount of

of free water depending on its density and other physical factors. While this phenomenon is not fully understood, Anderson assumed that snow will hold an amount of free water equal to about 2% of its water equivalent. In Amorochio's model a functional relationship between the density and water holding capacity (WHC) is assumed. However, for most cases, a value of 2% of the WHC is acceptably accurate and does not require a knowledge of the density.

Integration of Anderson's snowmelt model with the SWMM will provide acceptable accuracy both from the point of view of estimating snowmelt and accounting for temporal variation in the physical characteristics of the snowpack on an hourly basis during the storm period.

In addition to the above input parameters and the hydrometeorological assumptions previously described, the following assumptions can be made in order to simplify snowmelt computations for a one-event model:

- 1) Only the melt equations of Anderson's model will be required, since it can be assumed that for a one-event model the possibility of snowfall will not be accounted for.
- 2) Salting will not take place during the storm or melt period. Furthermore, it is assumed that the additional effect of salt melt is insignificant in relation to the total melt.
- 3) Snow removal from streets or parking lots will not take place during the storm or melt period.
- 4) Refreeze of the snowpack will not occur during the simulation period.
- 5) Attenuation and lag of free water available for runoff will be accounted for in the RUNOFF block of SWMM.
- 6) Frozen ground does not thaw during a one-event simulation.
- 7) An areal depletion curve for the watershed will be assumed available as input to the model.
- 8) The possibility of ground heat contributing to melt is considered insignificant for one event simulation.

It is readily apparent that reliable snow accumulation and melt measurements must be used in order to calibrate and validate the model. It is, therefore, recommended that studies of the areal distribution of the physical snowpack parameters and depletion characteristics be made for urban catchments. Such a measurement program should also incorporate research on the movement of melt water through a snowpack and the effect of frozen ground and slush layers on the amount and time of runoff. Measurements of infiltration rates in frozen and partially frozen ground should also be made. In view of the current paucity of available data to indicate otherwise, it will be assumed that the methodology presently used in the SWMM for accounting for infiltration will be applicable, provided the correct parameters reflecting frozen or partially frozen conditions are selected for the infiltration equation.

5. SNOW QUALITY - LITERATURE SURVEY

5. General

5.1.1 Introduction

Although the pollution of snow and melt waters is recognized as a serious problem, especially in the urban environment, the problem was not investigated in detail until recently and, therefore, the literature is rather limited. The main efforts to date have been to measure the actual amounts of various pollutants in snow. Very limited literature was found describing the modelling of pollutants in snow or in snowmelt waters.

The following is a list of the main pollutants which are found in snow:

chlorides; sulphates; nitrates; phosphates; suspended solids; organics; cyanide; oil; trash; soot; soil; phenol; metals (in both soluble and insoluble form) such as lead, iron, copper, zinc, cadmium, chromium, nickel, and manganese.

These substances are generally not characteristic of fresh falling snow but are mixed with the snow after precipitation. For all practical purposes, it is assumed that the pollutants are not significant in freshly fallen snow. However, it is worthwhile to mention the results of two quality studies of precipitating snow.

Shaw and Whelpdale [83] measured sulphate ion concentrations in snow precipitating in the western Lake Ontario region along a 100 km stretch of shoreline from Toronto to Niagara-on-the-Lake. The results showed that there is 1.7 to 4.1 mg/kg sulphate concentration in snow before it falls on the surface. The pH values and the specific conductance provide a good indication of the concentrations of sulphate ions and of organic compounds existing in precipitating snow. Daily sulphate deposition values were measured which gave a mean of $29 \text{ mg/m}^2/\text{day}$ ($\pm 77\%$).

These results are comparable with quality data obtained by Pearson and Fisher [84], although their values are averages and include snow, rain and dry deposition. Their average values indicated that $9\text{-}113 \text{ mg/m}^2/\text{day}$ of sulphate loads should be expected in precipitation near industrial areas. Sodium and chloride levels are significant in coastal areas.

Atmospheric pollution can reach the surface in precipitating rain and snow. Lead, nutrients, pesticides or other pollutants could also exist in falling snow, but no measurements are currently available.

Table 20 indicates the values of different pollutant concentrations found in snow samples collected from trucks and land disposal sites in the Metropolitan Toronto area [85].

TABLE 20. SNOW POLLUTANT CONCENTRATIONS MEASURED IN TORONTO

<u>Parameter</u>	<u>Concentration (ppm)</u>	<u>Loading lb/ton of snow</u>
Total solids	10,500	21
Chlorides	2,250	4.4
Total lead	9.8	0.02
Total iron	41.5	0.08
Total phosphorus	2.4	0.005
BOD ₅	57	0.114

Similarly, results of a recent study conducted by the Ontario Ministry of Environment gave the average values shown in Table 21 for different pollutants found in snow samples taken from roads during the winter 1973 - 74 in six municipalities of Ontario [86].

TABLE 21. SNOW POLLUTANT CONCENTRATIONS MEASURED IN DIFFERENT CITIES OF ONTARIO

<u>Municipality</u>	<u>BOD₅ (ppm)</u>	<u>Susp. Solids (ppm)</u>	<u>Chlor- ide (ppm)</u>	<u>Diss. Lead (ppm)</u>	<u>Total Phosphate (ppm)</u>	<u>Phenol (ppb)</u>
Thunder Bay	54	21,433	3,051			36
Timmins	15	28,767	505		0.97	25
Sault Ste. Marie	14	34,967	730			30
Toronto	21	-	11,318	0.34	14	115
London	31	12,100	1,490			29
Barrie	-	11,700	-			-

5.1.2 Sources of snow pollution

Possible sources of pollutants deposited in snow are road salts, de-icing chemical agents, combustion of leaded gasoline in motor vehicles, oils, greases, gasoline leaking from vehicles, rust and wear of car body parts, wear and tear on tires, washout of air pollution particles, combustion of coal and oil for heating, materials eroded from pavements, fecal droppings of animals, herbicides, pesticides, fertilizers, building and demolition waste, dust and dirt blown by the wind and debris dropped or scattered by individuals, etc. [17]. This list, although in no way complete, is an indication of numerous possible sources of pollution. The source and the quantity of pollutants from each source is directly related to the degree of urbanization and to the population densities.

Quality of the snow is determined by various sampling techniques reported in literature, such as scan sampling and other methods described in the EPA report [11].

5.1.3 Effect of traffic on snowmelt

Traffic is considered to be an important parameter when considering snow contamination and depletion. The heat generated by the friction of the tires on the pavement and the mechanical splashing of snow are the two primary means of removal associated with traffic. However, until the snow reaches a free water content of about 30%, or more, traffic will not effectively deplete snow from roadways [87]. To obtain 30% free water content in snow, it would be necessary to apply 220 pounds of salt per two-lane mile of road with one inch of snow at an air temperature of 40°F. According to J.L. Richards and Associates [88], the remaining snow will be removed by traffic whenever the traffic density is greater than 50 vehicles/hour.

5.2 Pollutants in Snow

5.2.1 De-icing salts

De-icing agents for removal of ice and snow from highways and streets are essential to wintertime road maintenance in most areas of Canada and the U.S.A. These de-icing agents are found to be the most significant in causing contamination and damage of groundwaters, public

water supplies, roadside wells, farm supply ponds, and roadside soil and vegetation. De-icers also contribute to deterioration of highway structures and pavements, and to accelerated corrosion of vehicles [89]. Various chemical de-icers are commercially available, including rock salt, calcium chloride and other chlorides, the common ammonium salts, various alcohols, glycerol, and special composition products. Furthermore, sodium chloride and calcium chloride are found to be used almost exclusively as de-icing agents because of their efficiency in melting ice and snow, availability, and relatively low material cost. These two salts are generally used separately, but may be mixed together to satisfy certain conditions [90, 91, 92, 93]. In ice control, sodium chloride is considered to be more effective over longer periods and cuts deeper, but the calcium salt reacts faster. Consequently, the two salts are mixed in different ratios, depending upon given weather conditions, so as to use the best characteristics of both chemicals. Many recommendations may be found in the literature on the optimum ratios of calcium to sodium mix [90, 94].

Highway salting rates in the range of 400 to 1,200 pounds of salt per mile of roadway per application are not uncommon in the U.S. Moreover, it has been found that many roads and highways in the U.S. may receive more than 20 tons salt per lane mile, or more than 100 tons per road mile, over the winter season [92, 94]. Similarly, the salt application rates suggested by the Ministry of Transportation and Communications are as follows [86]:

450 lb per application per two lane mile for rural roads; and,
800 lb per application per two lane mile for urban roads.

Furthermore, it has been reported that the salting rate varies with population density [86]. Some examples are given in Table 22.

TABLE 22. SALTING RATES USED IN ONTARIO

<u>Population Density</u> <u>(pop. per sq mile)</u>	<u>Rates of Salt Application</u> <u>(lb per app. per lane/mile)</u>
Less than 1,000	75 - 800
From 1,000 to 5,000	350 - 1,800
More than 5,000	400 - 1,200

Also, it has been reported that, except under very low temperatures (below 10°F) and very light traffic, the rate of ice or snow melting will primarily depend upon traffic volume rather than the melting properties of the de-icing chemicals used. Further, it has been shown that 600 pounds of sodium chloride applied per mile of 20 foot width road coated with 0.2 inch ice (or 2 inches of snow) would melt about 10 percent of this ice cover, which is found to be sufficient for maintaining bare pavement conditions [94].

For example, in the City of Halifax, salt or sand is generally applied to the bus routes and the traffic arteries during every winter storm event by the Works Department. Salt or sand is only seldom used for the residential streets. Table 23 shows the amount of salt and sand applied in the Halifax peninsula during the winter months of January through April, 1974. Salt and sand application rates on a street-by-street or storm-by-storm basis are not available [20].

TABLE 23. SAND AND SALT APPLICATION
IN HALIFAX PENINSULA

<u>Month</u>	<u>Ton/Mile</u>		<u>Snowfall</u>	<u>Days with Minimum Temperature</u>	
	<u>Sand</u>	<u>Salt</u>		<u><10°F</u>	<u><20°F</u>
January	6.49	49.12	11.6	13	19
February	3.06	53.42	40.3	8	19
March	2.13	12.97	8.5	3	15
April	0.12	2.72	4.0	0	0

NOTE: Quantities based on the City of Halifax Works Department estimate that 25% of sand applied city-wide is used on 60 miles of arterial streets in the peninsula, and that total salt usage is distributed on 90 miles of city arterial streets.

Street runoff from the melting of ice and snow containing chloride salts enters municipal sewage treatment plants and surface streams via combined and storm sewers and, hence, could constitute severe pollutional problems. Daily chloride loads were found to be 40 to 50 percent higher for winter months compared to summer months in municipal sewage at Milwaukee,

Wisconsin [93]. In Madison, Wisconsin, wintertime street runoff had chloride levels ranging up to 3,275 mg/l [93]. Street runoff samples collected from a downtown Chicago expressway in the winter of 1967 showed a chloride content from 11,000 to 25,000 mg/l [17, 95]. Table 24 illustrates some high chloride concentration values found in runoff at different locations [97].

TABLE 24. HIGH CHLORIDE VALUES IN RUNOFF

<u>Location</u>	<u>Source</u>	<u>Date</u>	<u>Chloride (mg/l)</u>	<u>Ref.</u>
Chippewa Falls, Wisc.	Highway	1956-1957	10,250	[92]
Madison, Wisc.	Street	1956-1957	3,275	[92]
Lake Monona, Wisc.	Snow pile	1956-1957	1,130	[92]
Chicago, Ill.	JFK Expressway	1966-1967	25,100	[17, 95]
Des Moines, Iowa	Cummins Pkwy. storm drain	1968-1969	2,720	[96]
Burlington, Ont.	Heavily travelled street in down- town	1974	7,750	[109]

Although the fate of de-icing salts following their application onto streets and highways is not well defined at present, it is known that a part of the applied salt may be stored in the soils, groundwater, and vegetation comprising the roadside environment. Hawkins [98] suggested that de-icing chemicals may also be stored on the street itself in the snow and ice cover, on the street surface, and directly within the street masonry concrete, cobbles and other street construction materials. Further, he concluded that these salts from the streets may enter into combined and storm sewers throughout the year.

In the Ottawa snow study [100] it was found that natural snow has an average chloride concentration of 5 mg/kg of snow, which is similar to results obtained in Montreal and Toronto, whereas in samples

along streets, the chloride concentration reached 4500 mg/kg of snow. The salts used for de-icing may eventually find their way into the groundwater by infiltration. A groundwater study in Massachusetts found that the chloride levels in groundwater increased from 10 mg/l in 1955 to 35 mg/l in 1970 as a result of a snow disposal site on land [101].

Hutchinson [102] studied the effect of road de-icing salts on the sodium and chloride levels in a) streams and rivers; b) private water supplies, wells near roadways; and, c) soils along highways. The study area was in Maine, where seven rivers, 100 wells and most highways were analyzed over a period of four years. Results indicated that:

- (i) Rivers and streams are not affected by highway salting since both chloride and sodium ion concentrations remained constant throughout the investigation period. Although the levels tend to rise downstream of storm sewer outlets, the average along the rivers for 27 stations were 3.4 and 1.5 ppm for sodium and chloride ions, respectively.
- (ii) Wells along Maine highways indicate that Na^+ and Cl^- levels are high, averaging 69 and 162 ppm, respectively. 25% of the wells were unfit for potable water supply because they exceeded the 250 ppm chloride limit.
- (iii) Na^+ and Cl^- levels in soils bordering highways are directly proportional to the length of time over which highways have been salted. In areas where salt has been applied for 20 years, the sodium levels have been affected to a distance of 60 ft from the highways and to a depth of 18 inches. Chloride levels in groundwater ranged from 10 to 2525 ppm.

A study in the suburban areas of Boston, Mass. [103] revealed that groundwater and wells were seriously affected by road salts. The average steady-state contamination of groundwater, at the current rates of salt application to roads, was about 160 mg/l sodium chloride (100 mg of chloride per litre). The salt level in wells in the vicinity of major highways rose to nearly four times the 160 ppm salt concentration.

Table 25 lists the mean concentrations of sodium and chloride measured in snow samples from different types of roads in various cities of Ontario [104].

TABLE 25. SODIUM AND CHLORIDE CONCENTRATIONS
IN SNOW FROM ROADS IN ONTARIO

	Sodium (mg/kg)				Chloride (mg/kg)				
	<u>Arterial</u>	<u>Second.</u>	<u>Resid.</u>	<u>Dump</u>	<u>Arterial</u>	<u>Second.</u>	<u>Resid.</u>	<u>Dump</u>	<u>Park</u>
Toronto					13325	9310		11840	14
Ottawa	2254	981	445		3321	1607	990	3965	
Windsor	3130	3557	489		4852	5357	856		
Barrie	300	61	81.5		600	94	126		
Timmins	942	234	118		1476	384	191		
Belleville	5115	1579	200		8114	2674	339		

5.2.2 Lead

Lead in snow is largely derived from the combustion of leaded gasoline. Approximately 2.4-4.8 gm lead is released into the atmosphere during combustion of one imperial gallon of gasoline. The lead in snow is generally insoluble and is found in suspended solids and roadside dirt. The Ottawa study found that there was less than 0.05 ppm lead in undisturbed natural snow on ground; however, during the Toronto Snow Disposal Study, lead levels as high as 0.39 ppm were found in natural snow in St. James Park, Toronto [105]. This higher level is probably due to higher traffic volumes in Toronto.

Time dependency tests of lead in a windrow showed wide variations but indicated that lead tends to accumulate when the windrow remains in the same place. The study clearly showed that lead concentrations in snow increased on heavily travelled streets. An important observation is that 95% of the total lead was in suspended solids; these lead particles did not migrate downwards through the snow but remained on the surface or came to the surface as snow melted [100].

Similarly, the location of the windrow also affects the lead concentrations, as shown in Table 26. These values were measured in windrows on different types of streets in Ottawa [100].

TABLE 26. TOTAL LEAD CONCENTRATION MEASURED IN WINDROWS IN OTTAWA

<u>Street Type</u>	<u>Mean Total Lead Concentration (mg/l)</u>
Residential	2.0
Industrial	4.7
Commercial	3.7
Freeway	102.0

An analysis of the snow during melting at the Mann Avenue disposal site in Ottawa indicated that snow in the upper surface had a black crust and contained 19.2 mg/kg lead, whereas the interior of snow pile had only 0.12 mg/kg lead. This dump site receives snow from the central business district; the runoff from the site contained 0.173 mg/l lead concentration. Another snow disposal site in Ottawa, the Woodroffe Ave. site, which receives basically residential and commercial street snow, had only 0.048 mg/l lead in the runoff, nearly four times less than the central district dump site [100].

Lead concentrations at various disposal sites in Ottawa are listed in Table 27.

TABLE 27. LEAD CONCENTRATION IN SNOW AT DISPOSAL SITES IN OTTAWA

	<u>Mean Lead content in snow (mg/kg)</u>	<u>District - land use from which snow is received</u>
Churchill Ave.	0.9	Parks, residential, parking lots
Woodroffe Ave.	1.1	Residential, commercial
Riverside-Vanier	3.3	Residential
Mann Ave.	4.4	Central business district
Riverside-Ottawa	4.5	Most arterials, resid., commercial
Bayview Ave.	6.0	Collectors & arterials, resid., comm.
Brewer Park	9.5	Collectors & arterials, resid., comm.

The runoff from disposal sites varies in lead concentration, primarily due to changes in the runoff rate. Moreover, it was found that more than 90 percent of the lead being deposited in dump sites was associated with the suspended solids. Some of these solids were carried away from the snow disposal site in the runoff to storm sewers and receiving waters. A mean lead concentration of 0.112 mg/l was noticed in snow dump runoff from 11 sites in Ottawa. Also, it was found that only 2.3 percent of the lead in snow dumps was escaping in the runoff [106]. Furthermore, a higher mean total lead concentration of 0.143 mg/l was measured in runoff being carried in storm sewers in the study area. These results indicate that one of the major contributors to the lead levels in the rivers of this study area is the runoff occurring from windrows and snow remaining along streets.

Lagerwerff and Specht [107] examined soils at 8, 17 and 32 m from the edge of highways of different traffic volumes (7500-48,000 cars/day) and found a decreasing lead concentration in soils with increasing distance from the roadside. The top 5 cm of soil showed the greatest increase in lead concentration. Studies by Motto et al [108] indicated that lead levels decreased logarithmically with distance from highway. The major effect of lead from the traffic was found in the top 2 inches of soil, within 30-60 metres from the roadside.

Lead concentration in soils at snow disposal sites have increased greatly. Table 28 shows the lead content in the top one inch of soil at five Ottawa dump sites [100]:

TABLE 28. LEAD CONCENTRATION IN SOIL AT DISPOSAL SITES IN OTTAWA

<u>Disposal Site</u>	<u>Average Lead Content mg/kg</u>
Riverside-Vanier	28.1
Grandeur	176
Stanley Park	263
Mann Avenue	438
Riverside-Ottawa	2270

Soil profile analyses at the Mann Avenue dump site indicated that lead was deposited in soil in discrete layers of 3/4 - 1 inch per year. The natural lead level of the soil at this site was 21 mg/kg; the soil was affected to a depth of 24 inches with highest concentrations in the top 2 inches [100].

A recent study performed in Halifax, N.S. found insoluble lead content in winter surface runoff as high as 0.95 mg/l in samples collected from residential streets. However, a maximum concentration of 0.15 mg/l was reported for the soluble lead content [20]. Similarly, a maximum lead concentration of 3.7 mg/l was found in the snow samples collected from different areas in Burlington during the winter months of 1974 [104].

LaBarre, Milne and Oliver [31] studied lead contamination of snow in Ottawa. They found that the level of lead in snow along city roads was roughly proportional to the traffic volume. The results of the detailed sampling are given in Table 29.

TABLE 29. LEAD CONTAMINATION OF SNOW IN OTTAWA

<u>Location</u>	<u>No. of Samples</u>	<u>Mean Lead Level</u> (mg/l)		<u>Total Sample</u>	<u>Range of Total Sample (mg/l)</u>
		<u>Filtrate</u>	<u>Particulate</u>		
Snow dump	149	.052	555	4.8	.02 -50
Highway	3	.060	3287	102	86 -113
Commercial street	41	.042	822	3.7	.02 -11.3
Industrial street	6	.048	935	4.7	.06 -14.3
Residential "	9	.014	1228	2.0	.12 -10.2
Roof samples	7	.041	-	0.10	.02 -.25
Snow dump runoff	39	.009	1322	0.11	.004-.51
Storm sewer runoff	50	.007	1791	0.13	.002-1.19
Raw wastewater	5	.026	479	0.09	.05 -.16
Treated wastewater	13	.027	448	0.06	.003-.14
Ottawa River	8	.006	69	0.03	.004-.046

It can be seen that the lead in the filtrate is very low, regardless of high concentrations in the particulate part of the samples. Comparison of snow dump runoff (0.11 mg/l) shows that, because the lead is present in the form of particulates, most of the lead is retained at the site after the snow has melted.

5.2.3 Other heavy metals

Heavy metals other than lead also have a high potential toxicity to various biological forms. Concentrations obtained from Ottawa and Toronto snow dump sites are given in Table 30 [100]:

TABLE 30. OTHER HEAVY METALS IN SNOW
MEASURED AT SNOW DUMP SITES

	<u>Ottawa</u>	<u>Toronto</u>
Cadmium	< .05	.05
Barium	0.50	not meas.
Zinc	0.60	7.31
Copper	0.19	< 0.41
Iron	30.0	45-53
Chromium	< .02	0.08
Arsenic	< .02	not meas.

In Table 31 are shown the concentrations of various heavy metals in snow and water samples collected from different areas in Burlington during the winter of 1974 [110].

TABLE 31. HEAVY METALS CONCENTRATIONS IN
SNOW MEASURED IN BURLINGTON, ONTARIO

	<u>Residential</u>	<u>Commercial</u>	<u>Heavily Travelled Street</u>
Cadmium	< .001-.009	< .001-.010	.003-.018
Barium	< .10-.16	< .10-.26	.26-.46
Zinc	.012-.86	.05-4.0	1.5-1.8
Copper	.001-.06	.005-.08	.05-.09
Chromium	< .001-.006	<.001-.008	.001-.11
Nickel	.001-.005	<.001-.07	.014-.07

Further measurements in Ottawa showed that, although most heavy metals are present in snow, they may not affect the receiving water bodies because they are mainly insoluble and only change the riverbed sediment concentrations.

5.2.4 Five-day biochemical oxygen demand (BOD₅)

The most widely used parameter of organic pollution applied to surface waters is the five-day BOD (BOD₅). The BOD measurement is significant in water quality management because it is used to determine the approximate quantity of oxygen that will be required to biologically stabilize the organic matter present. Results of several studies conducted at different locations to determine BOD₅ of snow are summarized in Table 32 [105, 109]:

TABLE 32. BOD₅ OF SNOW (mg/l)

	<u>Highway</u>	<u>Arterial</u>	<u>Secondary</u>	<u>Residential</u>	<u>Dumps</u>
Ottawa		16.6	13.2	5.5	15
Windsor		10.0	6.2	4.7	
Barrie		5.7	2.7	2.7	
Timmins		18.1	39.3	7.1	
Belleville		30.0	17.8	3.4	
Toronto		17.0	25.0		84
Ont. Highways	14.0				

The Halifax study indicated similar results, with BOD₅ values ranging from 5 to 48 mg/l measured in the winter surface runoff samples taken from residential streets [20].

5.2.5 Suspended solids

The suspended solids concentration, which reflects the amount of insoluble particles present in snow, may become very high following sanding and salting operations. Very high levels of suspended solids may significantly alter turbidity in the receiving water and generally degrade the aquatic environment. Table 33 shows the values of suspended

solids found in snow windrows in Ottawa central business districts [100]:

TABLE 33. SUSPENDED SOLIDS IN SNOW WINDROWS IN OTTAWA

<u>Location</u>	<u>Concentration (mg/kg)</u>
Arterial street	3570
Collector street	4020
Local residential street	2530
Parking lot	1620

Suspended solids concentrations at snow dump sites were found to be much higher. Further, it was found that the suspended solids basically remained in the upper black crust. This surface layer contained 567,000 mg/kg of snow and included sand and gravel mixed up from unpaved shoulders or ramps. The interior of the snow pile contained 7400 mg/kg. However, the runoff from the site had a very low suspended solids concentration of 96 mg/l. The receiving rivers seemed unaffected by suspended solids from dump sites.

In the City of Toronto, suspended solids concentrations in parks near Queen Street averaged 37 mg/kg, whereas in five dump sites a mean of 5180 mg/kg was recorded [106].

Further, surface runoff samples collected during the winter months in Halifax, N.S. showed suspended solids concentrations ranging from 40 to 430 mg/l and 128 to 750 mg/l for lightly and heavily travelled streets in a residential area, respectively [20].

5.2.6 Phosphates and nitrates

Phosphorus and nitrogen compounds are generally the most common nutrients present in snowmelt.

In snow windrows in Ottawa and Toronto, it was observed that insoluble phosphates concentrate in the upper layer while soluble phosphates can move down through the snow. The maximum total phosphate measured in Ottawa snow was 0.087 mg/kg in the streets and 3.6 mg/kg at dump sites [100]. On highways 0.036 mg/kg phosphate was measured.

Snow samples in Ottawa never contained more than 2 mg/l nitrate or Kjeldahl nitrogen and this pollutant was considered relatively insignificant.

Further, the Halifax study [20] found values of total phosphate concentration ranging from 0.2 to 0.7 ppm in surface runoff samples collected during winter months of 1974 and similarly showed values for nitrate and nitrite nitrogen ranging from 1.2 to 3.4 ppm.

Snow samples collected in Burlington during the winter of 1974 showed concentrations of total phosphorus and total Kjeldahl nitrogen ranging from 0.01 to 0.63 mg/l and <0.1 to 1.7 mg/l, respectively [103].

5.2.7 Oils and greases

Oils and greases are the waste products of internal combustion engines, and usually remain in the upper layers of snow and float on snowmelt runoff. In two Ottawa dump sites oil and grease samples had mean values of 28.6 and 19.6 mg/kg of snow, respectively. However, these concentrations decreased greatly as snowmelt started in spring. The upper black crust contained 1.4 mg/kg and the interior snow had only 0.4 mg oil per kilogram of snow [100].

Similarly, in snow samples collected from various areas of Burlington, oil and grease concentrations were found to range between 1.0 and 5.0 mg/kg [104].

5.2.8 Phenols

Phenolic substances, which are mainly derived from combustion, are another major pollutant. The mean level in five Toronto snow dump sites was found to be 0.114 mg/l, whereas in most samples from urban snow it ranged between 0.007 and 0.125 mg/l. Phenols were measured to be 0.003 mg/l in highway snow samples [105, 109].

5.2.9 Other pollution indicators - pH and conductivity in snow

Measurement of the pH of snow can be used to obtain an indication of inorganic compounds present.

Conductivity tests indicate the concentration of ions in the snow. Measurements in Ottawa, Windsor, Barrie, Timmins and Belleville

gave mean values ranging from 484 to 22375 $\mu\text{mho/cm}$ in snow from arterial roads. The conductivity of freshly falling snow is about 20 $\mu\text{mho/cm}$ [83, 109].

5.3 Snowmelt Runoff Quality Models

While there is no literature on snowmelt water quality models, there is a considerable amount of information concerning the relationships between dissolved constituents and discharge in streams.

A series of mixing models presented by Hall [111], has been successfully used for analyzing water quality data. These models are based on mass balance calculations along with derivations and solutions for certain assumptions about the mixing volumes and storage volume-discharge relationship. Details of the models and derivation of a number of equations from them can be found in reference [111].

The application of these mixing models seems to be rather limited as a large amount of flow and quality data are required to select an appropriate model.

In a study performed for the Salt Creek basin in the northeastern Illinois Metropolitan area to calculate road salt chloride budgets for the winter of 1972-73, the following chloride-discharge relationship was used to fit the collected data at various sections of the creek [112]:

$$C = A Q^n + C_o$$

Where C is the chloride concentration at a given point in the stream, Q is the stream discharge, A and n are constants, and C_o is a constant defining approximately the background concentration in a stream. The amount of chloride from sources other than road salts was estimated by using this equation. Thus, subtracting the background chloride loads from the chloride load applied, the amount of chloride removed by the creek during the study period was obtained. Further, it was found that 62 percent of the chloride was removed by the creek from the basin during the first six months, November 1, 1972 to April, 1973 of the study period. In addition, 10 percent of road salt chloride was removed during the next six month period.

It is apparent that an empirical relationship can be established, in a similar fashion, to determine the dissolved constituent concentration in urban runoff, based on a complete set of measurements.

5.4 Conclusions

Based on the literature review, the following conclusions may be drawn:

1. Within the past few years several studies have been conducted at various Canadian cities to determine the pollutorial aspects of snow disposal and, consequently, the effect of contaminated snowmelt water on the quality of receiving water bodies. Moreover, these reported studies have amply demonstrated that pollutant accumulation in snow increases in direct proportion to the vehicular traffic volume and degree of urbanization.
2. A number of contaminants in varying amounts can be expected in the snow deposited along a typical urban street, including chlorides, nitrites, phosphates, lead and other heavy metals, suspended solids, oil, and phenols.
3. Among the various contaminants generally found in the deposited snow and snowmelt water, chlorides and lead are reported to be the most serious and potentially hazardous pollutants. The mean values of chloride found at different cities in Canada ranged from 191 to 13,325 mg/l, depending upon the type of the roadway, lower values being for residential streets and higher values for highways. Similarly, a maximum lead concentration of 113 mg/l was measured in Ottawa on a major highway.
4. A large variation is reported in the concentrations of different pollutants generally found in deposited snow, depending upon a number of factors. For instance, snow deposited along the city arterials and in the central business district is found to be the most contaminated. Similarly, higher salt concentrations have been reported for snow deposited along the highways than for the snow deposited in residential areas.
5. Although the literature contains a reasonable amount of information about the characteristics and magnitude of various pollutants found

in the contaminated snow, sufficient data about the magnitude of contaminants which may enter the sewer system as a result of snow melting do not exist.

6. It has been found that a large portion of the insoluble pollutants would be retained at the site and only a relatively low amount would be washed off from snow dump sites.
7. Pollutants other than chlorides and lead are reported to be rather insignificant in causing pollutional problems to the receiving water bodies, which partly may be due to the low concentrations found in deposited snow.
8. As at present no information is available regarding snow quality modelling, a great need exists for a comprehensive data collection program to measure the following parameters, which would assist in the development of a snow quality model:
 - i) precipitation measurements;
 - ii) sand/salt application rates;
 - iii) snow removal practices;
 - iv) antecedent conditions;
 - v) analysis of snow and melt water samples; and,
 - vi) quantity of snow melt runoff.
9. Table 34 summarizes the observed range of concentrations for a number of contaminants measured in snow and snowmelt water at a variety of locations throughout Canada. Higher values were found at dump sites, while low values of pollutants were reported for residential neighbourhoods.

TABLE 34. REPORTED SNOW AND SNOWMELT WATER POLLUTANT CONCENTRATIONS

<u>Pollutant</u>	<u>Observed Range (mg/l)</u>
Chloride	7-15580
Lead	<0.02-113
BOD ₅	1.4 - 84
Suspended Solids	<1-4020
Organic Nitrogen	0.09-4.3
Nitrate-N	<0.01-1.5
Ammonia-N	0.01-0.3
Total Phosphate	<0.036-3.6
Sodium	3.6-9480
Phenol	.002-.125

6. DATA COLLECTION - STUDY AREAS

6.1 U.S. Data

The following tables and descriptions have been abstracted from a preliminary report on the establishment of an urban runoff data base [113]. This work is currently underway at the University of Florida. The most promising U.S. data sources are described in detail. To date, only four or five sets of data have been reduced and assembled at the University.

6.1.1 U.S. study areas

1) San Francisco, 3/75

Background and Type of Data - The City of San Francisco installed in 1971 an extensive network of telemetered tipping bucket rain gages and bubbler stage gages, such that transient rainfall patterns over the city and all flows at overflow locations may be monitored. The system has functioned since about November 1971 except that several stage gages have become inoperable during the last two years and have not yet been repaired. Extensive quantity data are stored on tapes and are available for the project. UF must do the reduction but the city has supplied some programs. The sewers are almost totally combined.

No quality data are currently being gathered, however, Hydrosience, Inc., gathered runoff and quality data at several overflow points in 1968-69. These data are published.

Quality of Data - Under the assumption that the stage-flow calibrations at bubbler locations are accurate, the current quantity data of the city are expected to be of excellent quality. The earlier Hydrosience data is of good quality.

<u>Sampling Agencies</u>	<u>Contacted?</u>
City of San Francisco Dept. of Public Works Bureau of Engineering Division of Sanitary Engineering	Yes (Harold C. Coffee, Jr.)

Hydrosience, Inc.	No
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Other Contacts

ASCE Urban Water Resources Research Program	Yes (M.B. McPherson)
Water Resources Engineers	Yes (R.P. Shubinski, L.A. Roesner)

OVERALL STATUS OF DATA SOURCES, MARCH 1975 (TAKEN FROM REF. 113)

<u>Location</u>	<u>Aware of Type of Data</u>	<u>Suitable for Modeling</u>	<u>Initially Contacted</u>	<u>Further Contact Define Data</u>	<u>Required to: Obtain Data</u>	<u>Possession of Data</u>	<u>Likelihood of Inclusion in Data Base</u>
San Francisco	Yes	Yes	Yes	No	Yes	Some	Good
Cincinnati	Yes	Yes	Yes	No	No	All	Fair
Philadelphia	Yes	Yes	Yes	Yes	Yes	Some	Fair
Washington, DC	Yes	No	No	No	No	Some	Poor
Lancaster	Yes	Yes	Yes	No	No	All	Good
Atlanta	Yes	Yes	Yes	No	No	All	Good
Denver	Yes	Yes	Yes	Yes	Yes	Some	Good
Seattle	Yes	Yes	Yes	No	Yes	None	Good
Lafayette	Yes	Yes	Yes	No	Yes	None	Fair
Portland	Yes	Yes	Yes	Yes	Yes	None	Fair
Racine	Yes	Yes	Yes	No	No	None	Good
Kenosha	Yes	No	Yes	No	No	None	Poor
Cleveland	Yes	Yes	Yes	Yes	Yes	None	Poor
Syracuse	Yes	?	Yes	Yes	Yes	None	Fair
Rochester	Yes	Yes	Yes	No	Yes	None	Good
Chicago	Yes	Yes	No	Yes	Yes	Some	Fair
Champaign- Urbana	Yes	Yes	Yes	Yes	Yes	None	Good
Milwaukee	No	?	No	Yes	Yes	None	Poor
Minneapolis	Yes	No	Yes	Yes	Yes	None	Poor
Lincoln	Yes	Yes	Yes	No	Yes	Some	Good
Los Angeles	Yes	Yes	Yes	Yes	Yes	None	Poor
Tallahassee	Yes	Yes	No	Yes	Yes	None	Fair
Broward County	Yes	Yes	Yes	No	Yes	None	Poor
Greenfield	Yes	Yes	Yes	Yes	Yes	None	Fair
Des Moines	Yes	Yes	No	Yes	Yes	None	Poor
Richmond	Yes	Yes	Yes	Yes	Yes	None	Poor
Passaic Valley	Yes	Doubtful	Yes	No	Yes	None	Poor
Baltimore	Yes	Yes	No	No	Yes	Some	Good
Woodlands	Yes	Yes	No	Yes	Yes	None	Fair
Louisville	Yes	Yes	No	Yes	Yes	None	Fair
Detroit	Yes	Yes	Yes	No	Yes	None	Fair
Colorado State Univ.	No	?	No	Yes	Yes	None	Poor
Duluth	No	?	No	Yes	Yes	None	Poor
Rutgers	No	?	No	Yes	Yes	None	Poor
Illinois State	Yes	Yes	Yes	No	Yes	None	Fair
Water Survey							
Roanoke	No	?	No	Yes	Yes	None	Poor

Status of Data UF has the Hydrosience report and will incorporate it into data base. UF has the programs from the city for reduction of their current quantity data but has not received any data yet. This will be done this spring. The city is very cooperative.

Likelihood of Inclusion in Data Base - Good for both Hydrosience and city data.

2) Cincinnati, 3/75

Background and Type of Data - The 2380-acre combined sewer area known as Bloody Run was studied by the University of Cincinnati during 1969-70, and quantity and quality data were collected for several storms. Some were used for original SWMM verification, as described in Volume II of the SWMM final report.

Quality of Data - There is some doubt as to the quality of the Cincinnati data since various investigators (Battelle Northwest and University of Cincinnati graduate students) have attempted to use portions of the results and discovered conflicting values for parameters between graphs and tables. There is also some question as to the accuracy of the flow measurements since recorded stages are very difficult to read at fractions of hours. UF will attempt to resolve these questions.

<u>Sampling Agencies</u>	<u>Contacted?</u>
University of Cincinnati	Yes (H. Preul)
<u>Other Contacts</u>	
Battelle Northwest	Yes (L. Kimmell)
H. Papadakis Michigan	No

Status of Data - UF has most of the original data (i.e., charts, notebooks, etc.) and reports and some subsequent information (University of Cincinnati thesis, data from Battelle Northwest). A large draft report containing tabulations of all data, along with computer cards has been requested from EPA, Edison. Without attempting to reduce all the original data a second time, the various published data will be spot checked against some original records to resolve inconsistencies. SWMM input data are contained in Volume I of the SWMM final report.

Likelihood of Inclusion in Data Base - Serious questions have arisen as to the validity of the data. Hence, the likelihood of its inclusion is only fair.

3) Philadelphia, 3/75

Background and Type of Data - The 5400 acre Wingohocking combined sewer area was monitored by the City of Philadelphia in the late 1960's. Some data were used for the original SWMM verification as reported in Volume II of the SWMM reports. Measured flows are available for several storms with limited quality data (mostly composites).

More recently, the city has attempted to establish a new monitoring program at several outfall locations, including frequent quality sampling. However, they have been seriously delayed because of hardware problems and storm damage.

Quality of Data - Quantity data from the early sampling program are of good value. Furthermore, four raingages are available to cover the 5400 acre catchment. Quality data are poor, however. Data from the current sampling program are expected to be very good, not obtainable during the course of this project.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Water Department City of Philadelphia (C. Guarino, J. Radziul)	No
<u>Other Contacts</u>	
University City Science Center	Yes (J. Haggerman)
Metcalf and Eddy (J. Lager)	No

Status of Data - UF has only a limited amount of the early sampling data. More effort is required to obtain the rest of it. SWMM input data are contained in Volume II of the SWMM Final Report. No published data are available for the current sampling program since it is only now resuming operations.

Likelihood of Inclusion in Data Base - Good for early quantity data. Nil for current data.

4) Lancaster, Pennsylvania, 3/75

Background and Type of Data - The 227 Stevens Avenue District is a combined sewer area that was the site of an EPA demonstration grant during 1971-74. Several storms were sampled from September 1973 through March 1974 in which flows may be obtained from continuous depth measurements within the sewer line, and quality data are available from an automatic sampler.

Quality of Data - Computation of "measured" flows is open to some debate as to interpretation of measured stages, but they are probably of reasonable accuracy. Measured quality data are good, and of sufficient frequency to be useful for modeling.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Dept. of Public Works City of Lancaster	Yes (A. Morris)
Meridian Engineering	Yes (R. Travaglini)

Other Contacts
None

Status of Data - UF has been associated with the project since its inception and possesses the original strip charts (for depths and some quality measurements) and other measured quality data. SWMM runs are currently being made to ensure accurate time correlation of measured rainfall and runoff data.

Likelihood of Inclusion in Data Base - Good.

5) Atlanta, 3/75

Background and Type of Data - For a project with the overall goal of improving DWF facilities and assessing stormwater pollution potential in the South River Basin, the firm of Black, Crow and Eidsness in 1973 measured the quantity and quality of three overflows serving large combined sewer areas southeast of downtown Atlanta. Unfortunately, accompanying rainfall measurements within the catchments were not made, and reliance must be placed upon airport readings six miles away or two closer USGS gages.

Quality of Data - The runoff and quality measurements are good, although quality measurements for some storms are infrequent (i.e., three of four samples per storm). Rainfall data are poor. However, since the study areas are triangulated by the three gages, it might be possible to analyze the data to develop a temporal and spatial storm pattern that would be satisfactory for modeling. UF's results with data from individual gages have been poor, as far as matching measured and predicted hydrographs using SWMM.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Black, Crow and Eidsness Engineers Atlanta	Yes (A.I. Perez)

Other Contacts
None

Status of Data - UF has all the data and is using it in constructing the initial data base.

Likelihood of Inclusion in Data Base - Good, although a clear warning will be necessary as to the evaluation of rainfall data.

6) Denver, 3/75

Background and Type of Data - The 2810 acre separate sewered Harvard Gulch catchment has had limited flow measurements taken by the USGS in cooperation with the Urban Drainage and Flood Control District. No quality data are available or planned, to UF's knowledge. Only four storms were monitored for the entire catchment, however, additional flow data are being gathered by the USGS for a 640 subarea. Several other catchments of various sizes are also being monitored (for flows and rainfalls) under the same program.

Quality of Data - The flow and rainfall data are gathered simultaneously at one point by combined instrumentation, and are of good quality.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Urban Drainage and Flood Control District	Yes (L.S. Tucker, B.S. Kolstad)
USGS	Yes (G.L. Ducret)

<u>Other Contacts</u>	
Wright-McLaughlin Engineers	No
Corps of Engineers, Omaha	Yes (C. Bueltel)

Status of Data - As part of its EPA "Nationwide Assessment" project, UF has the available verification and (SWMM) modeling data for Harvard Gulch. Data from other catchments may be obtained, but obtaining modeling data may be more difficult.

Likelihood of Inclusion in Data Base - Since Harvard Gulch is somewhat unique in its drainage facilities (extensive open channels, detention basins and other flood control facilities) the data are valuable, even though for only four storms. Hence the likelihood of inclusion is good.

7) Seattle, 3/75

Background and Type of Data - In an effort to obtain data suitable for model calibrations, Metro collected data from six storms for seven catchments of varying land use in 1973. (An earlier program had collected only generalized quality data unsuitable for modeling use.) Both continuous quantity and 15-minute quality data were gathered. (Apparently, flows may be conveniently obtained only at the same 15-minute intervals, however.)

Quality of Data - The data have been summarized in a recent report, and appear to be of good quality. Rainfall data are obtained from a 13-gage, city-wide network.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Municipality of Metropolitan Seattle (Metro)	Yes (G. Farris)
<u>Other Contacts</u>	
Water Resources Engineers	Yes (R. Fry, R.P. Shubinski, L.A. Roesner)

Status of Data - The detailed data may be obtained from Metro, as indicated in their summary report. UF has written for it.

Likelihood of Inclusion in Data Base - Good, if the detailed data are as good as the report indicates.

8) Lafayette, Indiana, 3/75

Background and Type of Data - The CE Department at Purdue has gathered rainfall runoff data for various catchments for a number of years. In particular, they have one 40 acre separate sewer catchment, fully urbanized, for which good rainfall-runoff measurements are available along with backup modeling data. No quality data are available, although a sampling program is currently underway on another catchment.

Quality of Data - The quantity data are of good quality and well suited to modeling applications.

<u>Sampling Agencies</u>	<u>Contacted?</u>
School of Civil Engineering Purdue University	Yes (J.W. Delleur)

Other Contacts
None

Status of Data - Professor Delleur had agreed to send UF data from the catchment discussed above (quantity only). However, in recent correspondence, he indicates a lack of manpower to prepare it prior to August. Negotiations will continue.

Likelihood of Inclusion in Data Base - Fair

9) Portland, Oregon 3/75

Background and Type of Data - The city, in cooperation with the USGS, is presently installing a telemetered network of 28 bubbler stage gages and 16 tipping bucket rain gages, similar to the San Francisco

installation. Although these data will probably arrive too late for our present project, one 80-acre urban catchment has already been monitored for flow and rainfall for several storms. No quality samples useful for modeling have been taken.

Quality of Data - UF presently has insufficient information on which to judge the quality of the data. However, it is apparently derived from strip charts of depth records coupled with a velocity meter, which should be of good quality.

<u>Sampling Agencies</u>	<u>Contacted?</u>
City of Portland Engineering Systems Group	Yes (D. Lorenzen)
USGS	Yes (D.J. Lystrom)

Other Contacts

None

Status of Data - UF is awaiting a response to its request for more information on the data.

Likelihood of Inclusion in Data Base - Fair.

10) Racine, 3/75

Background and Type of Data - As part of an EPA-sponsored project, Envirex has conducted an extensive study at an 800-acre combined sewer catchment in Racine. Detailed quantity and quality data are available for seven storms in 1973-74, with detailed quantity and composite quality for another 23. Data are available at two overflow points and upstream and downstream of treatment facilities. Three rain gages cover the 800 acres, and SWMM runs have already been made by Envirex for most storms, so these input data are also available.

Quality of Data - It is expected that these data will constitute some of the best available for the project, both in terms of accuracy and extent of sampling.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Envirex	Yes (T. Meinholz, C. Hansen)

Other Contacts

None

Status of Data - Envirex is just completing their draft final report on the Racine data and have promised UF a copy and full cooperation in sharing their data for the project.

Likelihood of Inclusion in Data Base - Good.

11) Cleveland, 3/75

Background and Type of Data - In 1966-67, the engineering firm of Havens and Emerson conducted measurements of quantity and quality at combined sewer overflow points for the 1836-acre Madison Study Area on the west side of Cleveland. Flows were calculated using a recording stage gage behind a weir and quality samples were taken every 15 minutes for several storms. Two recording rain gages were placed in the area.

Some more recent collection efforts may be underway under the direction of the city. Also, Havens and Emerson conducted a smaller sampling program in a combined sewer regulator point in the city of Avon Lake, 20 miles west of Cleveland. These data are too sparse to be useful, however.

Quality of Data - More information is required prior to a firm judgment. On the basis of portions of a report, the 1966-67 data look good.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Havens and Emerson	Yes (L.W. Curtis)
City of Cleveland (K. Pew)	No
<u>Other Contacts</u>	
Battelle Northwest (A. Brandstetter)	No
Watermation, Inc.	No

Status of Data - Follow up contact has been made with Havens and Emerson, but no response as of yet. Only a minor amount of summary data are presently in-house at UF. Contact needs to be made with the city to investigate current work.

Likelihood of Inclusion in Data Base - Poor-Fair.

12) Rochester, 3/75

Background and Type of Data - An extensive monitoring program is being conducted by O'Brien and Gere on 12 combined and two separate sewered catchments, varying from 150 to 3000 acres in size. Both continuous flow and frequent quality data are being gathered as well as rainfall from ten recording gages.

All data are being stored on magnetic tape and should be conveniently accessible at five-minute intervals, at least. A few samples of surface runoff are also being taken. The EPA-SWMM and WRE-SWMM are being run for several storms on several catchments, hence input data for these models will also be available.

Quality of Data - Measurements are expected to be quite accurate. Ultrasonic flow meters are being used in conjunction with stage recorders at four overflow points. Flows will be calculated from stage measurements over weirs at other points. Quality samples are taken at 20-minute intervals although it can take as long as ten minutes for the automatic sampler to fill the sample bottle.

<u>Sampling Agencies</u>	<u>Contacted?</u>
O'Brien and Gere, Inc.	Yes (S. Richardson)

Other Contacts
None

Status of Data - UF has followed up on its initial contact with O'Brien and Gere and hopes to receive first installments of data in the near future. Although they have been very cooperative, the main problem is actual assemblage and transmission of real data.

Likelihood of Inclusion in Data Base - Good.

13) Chicago, 3/75

Background and Type of Data - Quantity data from the Oakdale combined sewer catchment were presented in a 1968 ASCE report. These have been so widely used as to be of questionable value currently, but might still be included in the data base.

No sewer data exist, to UF's knowledge, unless some data gathered by Warren and Van Praag are relevant. There are also some USGS streamflow records available over areas too large to be useful for most urban model verification. These have been used, however, to verify Lanyon and Jackson's "Chicago Model" as reported in ASCE Urban Water Resources Research Program Technical Memo No. 20.

Quality of Data - Most of the Oakdale data are considered reliable, and unreliable events have generally been identified.

<u>Sampling Agencies</u>	<u>Contacted?</u>
USGS	No

Other Contacts
ASCE Urban Water Resources Research Program No

Metcalf and Eddy
(J. Lager) No

Warren and Van Praag No

Status of Data - Although it is unlikely that data subsequent to the Oakdale measurements exist, an investigation needs to be made.

Likelihood of Inclusion in Data Base - Good for Oakdale if time permits.

14) Champaign-Urbana, 3/75

Background and Type of Data - The 2290 acre Boneyard Creek catchment has been monitored for flows since 1948, with the most extensive rainfall data collected for the period 1960-65. The basin has a mixture of conduits and open channels. No quality data are available.

Quality of Data - Good, for both rainfall and runoff. Four weighing bucket rain gages are available prior to 1965, with only one since then.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Illinois State Water Survey	Yes (M. Terstriep)

USGS	No
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Other Contacts

University of Illinois (B. Yen)	No
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Status of Data - M. Terstriep has agreed to assemble and mail UF the data for Boneyard Creek, for most or all of the period 1960-65.

Likelihood of Inclusion in Data Base - Good.

15) Lincoln, 3/75

Background and Type of Data - Flow and quality measurements are available for three separate sewered catchments in Lincoln ranging from 70 to 375 acres. (A fourth catchment has very limited data.) Data were taken for 15 to 18 storms in 1972-73. Quality samples were taken by hand frequently during storms, and depths at control sections were read visually for flow calculations. A good definition of first flush effects is provided. Two nearby rain gages serve the three catchments.

Quality of Data - Flow calculations are based upon visually observed stages at a weir for one location and in conduits at two other locations. Since depths are probably accurate to an inch at most in the conduits, there is some question of accuracy here. Quality data are probably reasonably accurate, and have the advantage of quick sampling times, since they were "grabbed" by hand.

Sampling Agencies

Contacted?

Department of Civil Engineering
University of Nebraska

Yes (D. Anderson)

Water Resources Research Center
University of Nebraska

Yes (W. Viessman)

Other Contacts

None

Status of Data - UF has reports containing the detailed measurements of flow and quality. Rainfall data have been requested, since the reports only give totals and maximum intensities for each storm. Modeling data are available, but have not been requested.

Likelihood of Inclusion in Data Base - Good.

16) Los Angeles, 3/75

Background and Type of Data - The LA County Flood Control District (LACFCD) has continuous stage (and hence, flow) records for about six large (6-20 mile²) areas, dating back to 1930. Although these data may not be suitable for detailed models such as SWMM, they might be useful for models such as STORM and could possibly show effects of urbanization. In some cases, however, only daily discharges are available. Rain gages are located within each area. The LACFCD has taken no quality data.

The City of LA took flow measurements in the steep 252 acre separate sewer Echo Park Basin in Los Angeles over a period of 13 years. No quality samples were taken. The Illinois State Water Survey had some problems using these data, primarily because of the method of flow measurement (depth in a 51 inch sewer), and because of rainfall data (weighing bucket gage) too infrequent to define the very fast response of the steep basin.

Quality of Data - The LACFCD data are probably as accurate as can be expected for that type of measurement. Problems with the Echo Park data are mentioned above.

Sampling Agencies

Contacted?

LA County Flood Control District
Hydraulics Division

Yes (C.F. Eshelby,
H.A. Vance, G. Barber)

City of Los Angeles
Bureau of Engineering

Yes (A. Aarons)

Other Contacts

Illinois State Water Survey

Yes (M. Terstriep)

Status of Data - UF is still awaiting responses to its inquiries to the city, and awaiting documentation from its inquiries to the LACFCD.

Likelihood of Inclusion in Data Base - In view of the very long response time of the agencies involved, and possible problems with the Echo Park data, the likelihood of inclusion of data from either source is poor.

17) Tallahassee, 3/75

Background and Type of Data - During August 1973 to April 1974, Florida State University studied three catchments tributary to nearby Lake Jackson. Results from two of the catchments, one agricultural and forested (1563 acres) and one mostly urban (1780 acres) are available. The third includes drainage from a portion of Interstate 10, and data from it are not at the same level of analysis. The urban catchment has separate sewers. Both had rainfall-runoff measurements recorded on the same chart in a typical USGS installation.

Quality of Data - Both quality and quantity data appear to be good, although there may be some compositing of quality samples that would make them less valuable. Neither BOD nor COD were sampled.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Florida State University Department of Oceanography (R. Turner, T. Burton)	No

Other Contacts

None

Status of Data - UF needs to make direct contact with FSU to ascertain the availability of the data.

Likelihood of Inclusion in Data Base - Fair.

18) Broward County, Florida, 3/75

Background and Type of Data - The USGS, working for Broward County and the State Department of Transportation, began in April 1974 to sample quantity and quality at three locations near Fort Lauderdale. The three sites are 1) a 50 acre residential area, 2) 3000 feet of a four-lane highway, and 3) a small shopping center. Currently, most data are from the first site. The third site goes on-line during March 1975.

Quality of Data - All data appear to be of very good quality. Flows are measured using a modified venturi constriction and a bubbler gage. Rainfall is recorded from a tipping bucket gage. Quality samples are taken by an automatic sampler at 144 second intervals, (10 seconds are required to fill the bottle). Complete time synchronization is maintained by recording flows, rainfall and beginning of each quality sample on the same chart.

<u>Sampling Agencies</u>	<u>Contacted?</u>
USGS, Miami	Yes (C.B. Sherwood)
Broward County	No
Department of Transportation	No

Other Contacts

None

Status of Data - The USGS has had little time to devote to analysis of data collected so far due to pressures of other projects and budgetary constraints. Nor have the data been officially "blessed" by the sponsoring agencies (Broward County and the DOT). It is unlikely that either factor will change until spring or summer 1975.

Likelihood of Inclusion in Data Base - Although these are perhaps some of the best data discovered, it is unlikely that they will be available to UF during the course of the project. Hence, the likelihood of inclusion is poor.

19) Greenfield, Massachusetts, 3/75

Background and Type of Data - The University of Massachusetts is engaged in a sampling program sponsored by OWRR designed to measure the change in quantity and quality parameters in the Green River due to storm events in tributary portions of adjacent Greenfield. As part of this study, limited quantity and quality data have been collected for the 547-acre Maple Brook separate sewer catchment. The SWMM has been run on this catchment by University of Massachusetts as part of their study for selected storms, and these input data are available.

Quality of Data - There is some question concerning the flow calibration because of surcharging problems. As of summer, 1974, only solids had been measured (at ten-minute intervals) for quality sampling purposes.

<u>Sampling Agencies</u>	<u>Contacted?</u>
University of Massachusetts Dept. of Civil Engineering	Yes (P. Mangarella)

Other Contacts

None

Status of Data - UF needs to investigate further to learn more details of the program, and its emphasis. If of good quality, there should be little problem in obtaining the data.

Likelihood of Inclusion in Data Base - Fair.

20) Des Moines, 3/75

Background and Type of Data - Several combined and separate sewer discharges were sampled in Des Moines in 1968-69 as part of an EPA project. The project was designed to present an overview of wet-weather pollution problems in the city, and included collection of demographic, DWF and receiving water data. Several individual storms were sampled for quantity and quality at eight locations, and may be suitable for modeling purposes. Much of their data have been summarized in their completion report (EPA-R2-73-170, April 1974, "Combined Sewer Overflow Abatement Plan, Des Moines, Iowa," by P.L. Davis and F. Borchardt).

Quality of Data - The sampling program appears to have been conducted carefully. However, the hydrographs and pollutographs presented in the report indicate (perhaps) that a large sampling interval was used (on the order of hours).

<u>Sampling Agencies</u>	<u>Contacted?</u>
Henningson, Durham and Richardson, Inc. Omaha (P.L. Davis, F. Borchardt)	No

Other Contacts

None

Status of Data - UF's only source of information on Des Moines to date is the completion report, which, fortunately, contains a wealth of useful data. However, direct contact with HDR needs to be made.

Likelihood of Inclusion in Data Base - Even if these data prove suitable, there are likely to be severe logistical problems involved in actual acquisition. Hence, likelihood of inclusion is poor.

21) Richmond, 3/75

Background and Type of Data - A Step 1 EPA sponsored project is beginning in which a large monitoring program will sample from five catchments, four of which are of homogeneous land use. These four can thus be used to calibrate models for various land uses. Quality sampling will cover 10-12 parameters, and a network of 11 rain gages will be installed.

Unfortunately, the project is just beginning; bids for construction of monitoring sites are being let in March 1975. Data are expected by the end of the summer, but the usual delays in this sort of effort could easily push back that estimate.

Quality of Data - Expected to be good.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Hayes, Seay, Mattern and Mattern Roanoke (R. Perkins, S. Hubbell)	No
State Water Control Board Piedmont Regional Office Division of Special Projects (K. Das)	No

<u>Other Contacts</u>	
University City Science Center	Yes (J. Haggartman)

Status of Data - Since the project is just beginning, there are no data yet obtainable.

Likelihood of Inclusion in Data Base - Poor, due to time frame of project.

22) Baltimore, 3/75

Background and Type of Data - Rainfall-runoff data gathered for the Northwood and Gray Haven areas of Baltimore are described in detail in ASCE Memoranda, and have been widely used in urban runoff modeling studies. No quality data are available, nor have any recent data been collected, to UF's knowledge.

Quality of Data - Good although data for some storms, particularly for Northwood, may contain some errors.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Johns Hopkins University	No

<u>Other Contacts</u>	
ASCE Urban Water Resources Research Program	No

Status of Data - Both the Northwood and Gray Haven are well documented in two ASCE Memoranda.

Likelihood of Inclusion in Data Base - Good if time permits.

23) Woodlands, Texas, 3/75

Background and Type of Data - As part of a project aimed at "maximum utilization of water resources is a planned community," quantity and quality data are being gathered at the Woodlands area (a mostly natural catchment at present) and certain other catchments near Houston. A primary emphasis is to illustrate changes in water quality caused by impending urbanization, and how detrimental effects of urban runoff can be minimized by proper planning. On the basis of a few early progress reports (December 1973-April 1974) the sampling program appears to be extensive, but to UF's knowledge there are only a few detailed analyses of individual storms to date. Because of the natural environment that prevails at present, extensive biological monitoring is also underway. The SWMM will be run for the Woodlands area, so these input data will be available.

Quality of Data - Expected to be good.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Dept. of Environmental Science & Engineering Rice University	No
Espey, Huston & Associates	Yes (D. Winslow)

Other Contacts

None

Status of Data - Data collection is reportedly still at an early stage. However, UF needs to further investigate the current status.

Likelihood of Inclusion in Data Base - Poor-Fair.

24) Louisville, Kentucky, 3/75

Background and Type of Data - The Corps of Engineers monitored six areas ranging from 61 to 4,810 acres during 1945-1949. Five-minute rainfall data are available from ten gages to accompany the calibrated discharge measurements made in trunk sewers. No quality data are available.

Quality of Data - The rainfall-runoff data are felt to be relatively good.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Louisville District Corps of Engineers	No

Other Contacts

None

Status of Data - UF has not yet attempted to contact the Corps of Engineers in order to obtain the data.

Likelihood of Inclusion in Data Base - Fair.

25) Detroit, 3/75

Background and Type of Data - A network of 25 tipping-bucket rain gages and about 250 water level sensors are used to monitor rainfall and runoff in Detroit's combined sewer system. Rainfall and stage data are telemetered to a central location at five-minute intervals where they are currently being stored on a disk. At most locations, flows must be determined on the basis of depth in a conduit, leading to inaccuracies. Overflow sensors (event or no event) have been installed at most of the 72 overflows into the Detroit River.

Although there are considerable data being gathered, only one catchment, 1500 acre Oakwood has been studied extensively. At this location, the only outlet is through a pumping station, and flows may be accurately determined. Wayne State University has run SWMM for this catchment, so these data are available. Some surcharging occurs during high intensity rainfalls.

No quality data suitable for modeling are available. A monitoring program that would produce such data may begin this fall.

Quality of Data - The Oakwood data are of good quality, although the calibration procedure at Wayne State has been to compare predicted and measured pumping times and volumes. At other locations in Detroit, there are questions about the accuracy of flow data derived from stages.

Sampling Agencies

Contacted?

Detroit Metro Water Department Yes (R. Skrentner)

Wayne State University Yes (J. Anderson)
Department of Civil Engineering

Other Contacts

None

Status of Data - If approval is granted from higher authorities of the Water Department, they will send us all useful Oakwood data along with modeling input data that may be conveniently reproduced. Permission will also be requested from Wayne State to obtain the SWMM input data.

Likelihood of Inclusion in Data Base - Fair.

26) Illinois State Water Survey, 3/75

Background and Type of Data - Except for some association with the Boneyard Creek data, the Illinois State Water Survey has not taken samples themselves. However, they have assembled an enviable group of data for testing of their ILLUDAS model, and reported on these data in their Bulletin 58. Quantity data are presented from 23 basins, some of which are included in this UF progress report, others not.

Quality of Data - Most data used by the Illinois State Water Survey were of good quality.

<u>Sampling Agencies</u>	<u>Contacted?</u>
Illinois State Water Survey	Yes (M. Terstriep)

Other Contacts

None

Status of Data - UF has discussed various data sources contained in the ILLUDAS report with M. Terstriep. UF must follow up and make contacts with the individual sources.

Likelihood of Inclusion in Data Base - Good, for some sources; poor for others.

6.2 Canadian Study Areas

The principal Canadian study areas are described in the following sections.

6.2.1 West Toronto SWMM study area (quantity study)

6.2.1.1 Description of study area. The West Toronto study area is located in the City of Toronto, bounded by Bloor Street West, the Humber Valley, the City limits in the North, and Westmoreland Street in the East. The total population is 84,364 or 36 persons per acre.

The study area (2330 acres) has a combined sewer drainage system and is drained to Parkside Drive, where dry weather flow discharges to the mid-Toronto interceptor, and the overflow goes into a 9' circular outfall pipe. This 9' diameter storm outflow discharges into Humber Bay, Lake Ontario, over a length of 5230 ft, and no

backwater effects have been determined at the gauging site. Upstream of the 9' storm overflow pipe, there are three sewer pipes: a 78" x 60" basket handle shape coming in from Bloor Street West; a 111" x 111" circular sewer; and, a 45" x 36" eggshaped sewer running down Parkside Drive. All sewers are intercepted by a system of weirs which divert dry weather flow to a 36" diameter pipe going to the mid-Toronto interceptor. Part of the storm overflow is stored in standby tanks (total capacity of 100,000 cu ft) for time delayed release through a 15" pipe, running under the 9' sewer. Currently, these standby tanks are inadequate and fill very soon after a storm event begins. In the near future, Metro Toronto will probably remove them from the storm overflow system at Parkside Drive.

Overflow level is measured downstream of the standby tanks. No dry weather flow measurements existed prior to October 1, 1974, when Metro Toronto began measurements of dry weather flow depth in the 36" sewer going to the mid-Toronto interceptor.

6.2.1.2 Data sources and data description. The City of Toronto, Department of Public Works, furnished maps of the sewer system, street maps with spot elevations also showing house and industrial area locations and flow charts for overflow depths measured in the 9' sewer. Flow depths in the 9' sewer are measured by an air bubble gauge (Arkon Recorder - manufactured by a British firm, Walker Crosweller) equipped with motor, compressor, etc. The gauge records continuously a full month of data which can easily be read into five-minute intervals.

Dorsch Consult furnished maps of the sewer system, with a detailed listing of some 2700 pipe segments. Data, such as sewer shapes, sizes, lengths, invert elevation upstream and downstream percentage of impervious area, population density, etc. were obtained from these listings.

Rainfall data were obtained from the Atmospheric Environment Service, Environment Canada. One tipping bucket rainfall recording gauge exists within the study area (Old Weston Road). A similar rain gauge (Bloor gauge) is located a distance of 3.69 miles to the south-east. Data from daily rainfall charts at ten-minutes resolution, which can be interpolated for five-minute intervals, as well as hourly summarized data, were collected.

In addition to discussion of dry weather flow at the outlet, there are four other locations at which some flow is diverted from the drainage system. No flow measurements were available in any of these diversion structures. In order to reconstitute the entire storm flow from the West Toronto area, an attempt was made to estimate the capacity of each of the diversions, based upon the physical dimensions of the diverting weirs and conduits. It was estimated that the maximum total flow diverted by all structures during a storm event would be approximately 150 cfs. In order to adjust the measured overflows for the intercepted and diverted flows, a rough approximation table was prepared:

<u>Measured Overflow</u>	<u>Estimated Diversion</u>
0 - 500 cfs	150 cfs
500 - 1000 cfs	100 cfs
greater than 1000 cfs	50 cfs

A similar approximation was used for the 5400 acre Wingohocking area, which was used in the original SWMM verification. Applying these diversion allowances to the overflow hydrographs in the 9' outfall sewer provided the outflow hydrographs used in Volume 1, the Final Report for the study.

6.2.2 Winnipeg quantity and quality measurements

The measurement program was conducted by the City of Winnipeg Waterworks, Waste and Disposal Division, in the summers of 1969 to 1971. The program covered six districts, all having combined sewer systems. The flow measurement devices differ from one district to another; however, in all the systems except in the Mission District the measurements were taken in the main interceptor upstream of the overflow structure. A tipping bucket rainfall gauge was temporarily operated in each district during the study program period. Unfortunately, the strip charts have been misplaced in two recent moves by the local meteorological branch office. However, the charts from three other gauging stations in Winnipeg, operated by the Atmospheric Environment Service, are available.

Up to twelve separate ten-minute increment samples were gathered during periods of high flows and analysed for BOD, SS and total phosphates. Because of the physical limitations of the sampling system, only two hours of samples from each storm were generally obtained. Copies of the laboratory analyses are available. The quality and flow data were calculated to develop total load data, and plotted in the form of hydrographs and pollutographs. The total storm loadings were developed from projections of storm loads to normal dry weather flow values before and after the storms. Flows and loadings at these times were computed from diurnal patterns established during dry weather flow testing.

7. TREATMENT PROCESSES

7.1 Introduction

There are a fairly limited amount of data describing the treatment of storm and combined storm flows available to the modeller. This means that most treatment models are based at least in part on data collected at sanitary and industrial treatment plants. Generally, sanitary and industrial wastes are more soluble and/or flocculent than storm wastewaters, which tend to be insoluble and particulate. Combined wastes obviously display both sets of waste characteristics to a varying extent.

Most equations formulated to represent actual treatment processes were developed for steady state conditions. The waste stream characteristics of storm flows show a marked fluctuation with the progress of a storm event and are best described by dynamic equations. However, the formulation of these dynamic equations requires large amounts of data from pilot and full scale facilities. It seems likely that there will be a considerable time lag before all treatment processes are rigorously analysed and new models constructed.

The treatment model in the SWMM is essentially a tool for the initial analysis of different combinations of treatment units. BOD, SS and coliforms are traced through the treatment processes in the model. Other potentially important pollutants, such as nutrients, phenols and heavy metals are not considered. The treatment processes provide fixed percentage removals of the constituents from the inflow stream in each time step (subject to various minimum outflow concentration constraints). Obviously, this is somewhat simplistic as removals vary in different concentration ranges for specific waste streams.

Cost estimates are generated by a SWMM subroutine. Again, these are fairly approximate as there is not an extensive data base describing existing storm water treatment facilities. Most of the available data are from relatively small installations and, consequently, additional inaccuracies are involved when extrapolating the cost estimates to high design flows. The value of the treatment and

cost routines in the SWMM is in the planning stage. Various combinations of treatment options may be rapidly assessed and initial estimates of potential efficiency and cost assigned to these combinations.

The following sections are devoted to:

- a) a summary of the treatment processes available in SWMM; and,
- b) a review of current literature and modifications to the treatment model.

7.2 Treatment Process in the SWMM

The model initially sizes a treatment unit according to the peak hydraulic flow to that unit. The final design flow for the complete treatment plant is normally based on specific unit sizes and adjusted to the closest of the following allowable design capacities, in mgd*: 5, 10, 15, 20, 25, 30, 35, 50, 75, 100, 125, 150, 200, 250, 300, 350, 400, 450 or 500. In a few of the units (e.g. microstrainers), flow may be partially by-passed from the unit and recombined after treatment if the hydraulic loading becomes excessive.

Treatments that have been incorporated into the model are listed below:

1. Storage/sedimentation
2. Screening & filtering units
 - A. bar racks
 - B. fine screens
 - C. microstrainers
 - D. effluent screens
 - E. high rate filters
3. Concentrating units
 - A. swirl concentrator
 - B. dissolved air flotation
 - C. sedimentation
4. Biological treatment

* all volumes in U.S. gallons

5. Disinfection

- A. contact tank
- B. high rate disinfection

The above list represents most of the current potential forms of storm water treatment. Many modified forms of the above treatments have been used (e.g. hydrosieves), but very limited information is available and, therefore, no attempt has been made to develop the appropriate treatment equations.

7.2.1 Storage/sedimentation processes

Storage itself is not a treatment, but of course, most storage units provide the quiescent conditions necessary for sedimentation. The original SWM Model [1] provided for in-line storage ahead of treatment and allowed the user to select: the size of the storage basin, the amount or depth of water initially in the basin (to allow for analysis of multiple storm events), and one of two mixing regimes, i.e. ideal completely mixed flow or plug flow. Later versions of the model also allow for off-line storage.

Storage is a convenient way of attenuating peak flows to treatment, thereby reducing the size and cost of subsequent treatment options. Also, eccentric concentrations of wastes may be reduced to more uniform concentrations in the storage basin. This has the additional benefit of reducing large "instantaneous" solids loading to subsequent treatment options and increasing the effectiveness of the treatment processes.

At present, equations reflecting treatment processes are almost entirely based on average or quasi-steady state conditions and not transient state conditions. When storage is provided for attenuation of peak flows and concentrations, then more uniform conditions persist, and these equations would, therefore, be expected to produce more meaningful results. Presently, there are techniques available to classify mixing regimes subsequent to constrictions of a treatment unit. This is achieved by comparing dye tracings from the storage unit against theoretical distributions. Although this is

a good approach for system evaluation, construction of a unit precedes the establishing of the missing regime rather than vice versa. Information relating flow regimes (or a combination of flow regimes and associated dead spaces) to basin size and shape is needed before further modifications to the storage block in the program are warranted. (See also Levenspiel [114])

The equation used to determine SS and BOD removals in the Canadian version of the SWMM is based on the equation developed by Smith [28]. The settling efficiency is given by:

$$\eta = 0.82e^{-Q/2780} \quad (1)$$

where: Q is the overflow rate in gpd/ft².

7.2.2 Screening and filtering processes

The original model provided for four types of screening: bar racks, fine screens, microstrainers, and effluent screens. The suspended solids removal is, in part, dependent upon the size of the screen opening. The first three types of screens mentioned represent a range of sizes from large openings (three-inch clear space) to small openings (as low as 15 microns), the latter being intended only for removal of large floatable objects.

Present research and technology stipulate that removal rates are dependent on the following criteria:

- hydraulic loading;
- solids loading;
- differential head (dictated by the rotation speed);
- screen size;
- nature of the waste constituents (particulate or flocculent); and,
- chemical additions.

a) Bar racks - The original model provided for bar racks and dictated that all treatment systems would require these, except when storage preceded treatment. Design and cost calculations were developed according to assumptions that:

- the bars are spaced with 1-inch clear openings on 2-inch centres;
- the bar rack is mechanically cleaned and operated by a float mechanism;
- units are sized for a capacity of 240 cfs/bar rack (unit 8 ft by 10 ft at average velocity of 3 fps) but the number is limited to a minimum of two units; and,
- the bar racks remove 45 lb SS/mgal (based on 6 cu ft solids removed/mgal, weighing 50 lb/cu ft, containing 85% moisture), 2.25 lb BOD/mgal (based on 5% SS removed) and no coliforms.

This information was based on findings at municipal wastewater sewage treatment plants [1]. Research indicates that no further data or information on storm or combined storm water are available. Since the above parameters are reasonable values and do not affect waste stream concentrations, they remain unchanged in the Canadian model.

b) Fine screens - The original model developed for fine screens used results from a pilot plant design for treatment of combined storm waters, including treatment by dissolved air flotation. Design computations were developed using assumptions that:

- the fine screens are designed for a hydraulic loading of 50 gpm/ft²;
- a 50 mesh screen is used and a minimum of two screens is required;
- SS removal equals 27% of the inflow concentration while BOD removal equals 22%; and,
- backwash rate equals 0.75% of inflow.

Tests have indicated increased removal efficiencies with increased chemical addition, decreased screen size, increased loadings, and increased differential heads. Data from pilot plants indicate that during the first flush, SS and BOD removals increase by 9% and

5% respectively. These increases are due to the additional filtering potential of solids on the filter media [115,116]. The nature of the waste, i.e. flocculent, particulate, etc., dictates the particle resistance to shear. Consequently, hydraulic loading affects the removal efficiency.

Chemical addition may increase removal rates either by combining with, or forming separately, a supporting network that acts as an additional filtering screen. However, some chemicals react to form a more flocculent network that is even more susceptible to hydraulic shear.

Generally, the literature indicates a typical maximum hydraulic loading of 40 gpm/ft² with a screen size equal to a 50 mesh and a hydraulic differential head of 13 inches for these units. At these conditions, both SS and BOD removals would be in the order of 27% [117, 118, 119].

Drum rotation speed controls the solids loading to the rotating drum screens. It was found that 1.2 lb of dry solids/100 ft² of screen media (submerged) produced a head differential of 13 inches. Solids loading is estimated by the equation:

$$L_s = F_s R / r A_D \quad (2)$$

where: L_s = solids loading/100 ft²
 R = screen removal efficiency (%)
 F_s = feed solids into screen (lb/min)
 r = drum rotation (rpm)
 A_D = total surface area of screen.

With drum rotation speeds of 2 to 12 rpm, a removal efficiency of 35% is recommended [115].

Future equations should be developed to include all design parameters. Presently, it appears that the original SS removal rate is low when compared to results from units.

Consequently, in the Canadian model, the removal rate has been increased to 35%. The result of such action would be that greater importance would be placed on fine screens as a storm water treatment unit, since this action effectively decreases the ratio of cost-to-pollution abatement [119].

The BOD removal rate remains at 22% in the Canadian version since this appears to be a representative average of a wide variation of reported removal rates for fine screens.

c) Microstrainers - The original report by Metcalf and Eddy [1] indicated that the model should restrict flow rates through the unit to 40 gpm/ft^2 , and/or SS to be treated to a minimum level of 252 mg/l. Values in excess of this would actuate by-passing. The combination of by-passed and treated flow would be used to determine the overall performance of the unit.

A correction factor was introduced to generalize the removal equations in order that watersheds other than the watershed in which the removal equations were developed could be studied. Suspended solids removal efficiencies were developed from the prototype unit at Philadelphia by using linear correlation on the collected data. These equations were presented as:

$$\text{SS removal} = \text{SS}_{\text{INFLOW}} - 35 \quad \text{for } \text{SS}_{\text{conc.}} > 70 \quad (3)$$

$$\text{SS removal} = (\text{SS}_{\text{INFLOW}})^2 - 140 \quad \text{for } \text{SS}_{\text{conc.}} \leq 70 \quad (4)$$

BOD removal was assumed to be 80% of the SS removal. In the model, the hydraulic loading for the units was based on a filtrability index (I) of 2.43.

A review of present practice indicates that the method of determining the filterability index does not reflect the operating sequence of a microstrainer. Mixon determined that the surface areas calculated using this index were 30% over-designed when compared to a more appropriate theoretical development [121]. Glover and Herbert abandoned this index in favour of one developed in their study [116].

Pollutech evaluated a microstrainer with a 23 micron screen, loaded in the range of 1.5 - 6.0 gpm/ft² with a differential head of 4-7 inches [122]. This report indicated a decline in efficiency with increased SS concentration, but cites the fact that the first half of the study was run with domestic waste and the second half involved wastewater containing excessive silts and colloids.

Glover and Herbert indicated no correlation between BOD removals and SS removals, and suggested that a straight percentage removal criteria is not applicable to microstrainers. The report does indicate SS reductions from up to 700 mg/l to about 45 mg/l at hydraulic loadings in the range of 35-45 gpm/ft² and a head differential of 24 inches.

Diaper and Glover reported SS removals in the order of 78-98% with 91% being an average for combined storm wastewaters. Filtration rates ranged from 1.3 - 46 gpm/ft² using a 23 micron screen at differential heads up to 24 inches [118]. These and other reports indicate design parameters identical with those for fine filters except that the filter holes in the latter case are much smaller.

Considering the amount of data available, it is recommended that the original equations be retained, with appropriate modifications when additional information is available. The existing equations do predict adequate removal of SS when the microstrainers are operated under assumed operating conditions. Future equations should reflect a broader range of operating conditions and associated removal rates.

It should be noted that the updated versions of the SWMM do not by-pass flow when high SS concentrations are introduced. This is consistent with operating practice since an increase in drum rotation speed can be used to prevent flooding due to excessive solids buildup on the filter.

(d) Effluent screens - The treatment of a waste stream with effluent screens was originally used for the removal of unsightly materials and to render the waters aesthetically acceptable. It is

included in the model only for costing purposes since it presents no reduction of the waste parameters. The model assumes the capacity of these screens to be 450 gpm/ft^2 with a minimum of two units required. Screens are actually #6 mesh and the volume of screenings are estimated at 0.05 ft^3 per million gallons.

e) High rate filters - The original model allows the user to select the maximum operating rate for the filter, the maximum solids loading to the filter, and the option of chemical addition. Removal rates are based on test data from filters loaded at 20 gpm/ft^2 , and allow maximum SS and BOD reductions without chemical addition in the order of 80% and 50%, respectively, and 95% and 80%, respectively, with chemical addition. Furthermore, the efficiencies assumed drop to half the above values when the filter reaches 50% of the solids holding capacity. Additional removals due to chemical addition are based on the use of 150 mg/l of alum and 4 mg/l of flocculent aid. Headloss is calculated by Rose's equation, with no consideration for the underdrain system. It was assumed that headloss on the clean filter equals 40% of the maximum head at the design flow rate. Headloss is a function of solids and hydraulic loading and is calculated by the following equation:

$$H_{\text{loss}} = q/q_m \times S/S_{q_m} \times 0.6 H_m \quad (5)$$

where: H_{loss} = headloss due to clogging,
 q = flow rate,
 q_m = design flow rate,
 S = integrated sum of the solids removed in each time step, lb/ft^2 ,
 S_{q_m} = solids holding capacity of the filter
 H_m = maximum head at the design rate

The backwash was assumed to be 15 gpm/ft^2 for 10 minutes.

Further research has indicated that the above removal rates are achieved with hydraulic loading rates of 8 gpm/ft^2 at five foot headlosses. However, these removals decrease at high flow rates. Other results reflect similar removals using chemical additions of

30 mg/l of alum and 1 mg/l of polyelectrolyte. The media used that produced "optimum" conditions in one particular filter was No. 3 Anthracite over No. 612 Sand [123].

Filtering efficiencies would be expected to be based on the following parameters:

- nature of the particles to be removed (particulate or flocculent);
- filter media;
- chemical addition;
- headloss through the filter;
- flow rate through the filter; and,
- type and amount of solids trapped in the filter.

Future equations should include these parameters.

Although much information has been acquired, further information over a broad range of loadings, chemicals used, and other design criteria is necessary for the establishment of definite values for pollutants removal. It is important to note that Nebolsine et al [123] indicated that there was no correlation between BOD removal and filtration rate.

It is recommended that the existing equations developed in the original model be used for the Canadian version. These equations provide for consideration of many parameters needed for accurate predictions of pollutant removal and give representative results, useful at the planning stage.

7.2.3 Concentrating units

The three treatment units included in this section, swirl concentrator, dissolved air flotation, and sedimentation, differ from screening and filtering in that solids are removed by overcoming or utilizing gravitational forces.

a) Swirl concentrator - Recent modifications to the original model included the addition of the swirl concentrator. The swirl concentrator has been shown to be an effective treatment process for combined storm waters containing grit particles larger than 0.35 mm and settleable solids larger than 1.0 mm. Smaller percentages of finer materials would also be removed to a lesser extent. Separation

efficiency curves indicate removals up to 90% of the total settleable solids entering the unit. Percent removal has been correlated with flow rate for various unit capacities (Sullivan [124]).

In the study by Sullivan, the size range of particles considered represented 67% (by weight) of the materials in combined sewage from one locality. The efficiency of the swirl concentrator is sensitive to the inflow particle size distribution. Further investigations are proceeding in order to determine the optimum size of swirl concentrator for fine particles. Such considerations lead to two such units - one for grit and one for fines - for the treatment of storm waters.

Presently, the unit has been modelled in such a way that, given the flow, the size of the swirl concentrator, the particle sizes and specific gravities, and the fraction of the particles to each size, the efficiency of settleable solids removal can be computed (Heaney and Huber [28]).

The model calculates the percent removal of settleable solids according to the following steps:

- (i) Particles settling velocity, V_s , is determined by an iterative procedure. Initially, velocity is computed using Stokes' law:

$$V_s = \frac{g}{18} (S_s - 1) \frac{d^2}{x} \quad (6)$$

where: g = the gravitational acceleration,
 x = the kinematic viscosity of the water,
 S_s = the specific gravity,
 d = diameter of the particle.

Using V_s , the Reynolds Number, R , and the drag coefficient, C_D , are computed by the equations:

$$R = \frac{V_s d}{x} \quad (7)$$

$$C_D = \frac{24}{R} + \frac{3}{R} + 0.34 \quad (8)$$

The particle settling velocity is then computed again using the following equation:

$$V_s = \frac{4}{3} \frac{g}{C_D} (S_s - 1)d \quad (\text{cm/sec}) \quad (9)$$

These equations are then used iteratively until the values of V_s agree within 0.01 cm/sec.

- (ii) In order to use the curves developed in the APWA report [17], it is necessary to convert the particle settling velocity to the original 36' diameter swirl concentrator prototype settling velocity by applying the correction factor as follows:

$$V_s \text{ proto. (ft/sec)} = \frac{V_s}{30.48} \left(\frac{36}{D} \right)^{1/2} \quad (10)$$

where D is the design swirl concentrator diameter in feet and V_s is in cm/sec.

- (iii) Also, one must convert the design flow rate to the original prototype flow rate by applying the correction factor as follows:

$$Q_{\text{proto}} = Q_{\text{design}} \times \left(\frac{36}{D} \right)^{5/2} \quad (11)$$

- (iv) The program then uses simulated curves similar to the curves developed in the APWA report to compute the efficiencies.
- (v) The percent removal for that size range is multiplied by the fraction of particles in that size range to the total percent removal for that particle size.
- (vi) This procedure is repeated for each particle size to obtain the total percent removal.
- (vii) Since the model was developed for settleable solids, a correction factor of 0.6 is used to convert for SS removal.
- (viii) Since BOD can consist of contributions due to suspended organic solids as well as dissolved organic solids, a correction factor is applied to the SS removal to reflect

this BOD removal. Since this information reflects the most up-to-date information, no other modifications are suggested.

b) Dissolved air flotation - In the original model, the overflow rate, percent recycle, and tank depths were all input terms. Removal efficiencies were assumed to be a function of SS concentrations, overflow rates, and chemical addition. BOD removal efficiencies were based on a fixed percentage of the SS efficiencies. The model restricts the SS and BOD removal efficiencies to 20-82% and 18-60%, respectively. The equations are expressed as:

$$\begin{aligned} \text{Fractional SS removal} = & 0.656 + \frac{0.06 \times \text{SS conc.}}{190} \\ & - \frac{0.4 \times (\text{overflow} - 100)}{7000} + \frac{2000 - \text{overflow}}{100,000} \end{aligned} \quad (12)$$

$$\begin{aligned} \text{Fractional BOD removal} = & 0.59 + \frac{0.05 \times \text{BOD conc.}}{100} \\ & - \frac{0.36 \times (\text{overflow} - 1000)}{7000} + (0.02 \times I_{\text{chem}}) \end{aligned} \quad (13)$$

where I_{chem} equals 0 or 1.

Research has indicated that the process elements associated with dissolved air flotation that affect SS removal are [115]:

- flow pressurization;
- air introduction;
- air solution;
- pressure reduction and bubble formation;
- bubble/solids attachment;
- solids/liquid separation; and,
- separated solids removal.

Flow pressurization may be total pressurization of the entire volume of raw waste; split flow, or a portion of the raw waste pressurized and blended with the remaining waste streams; or effluent pressurization, or a portion of the waste effluent pressurized and blended with the influent waste stream.

The performance of a flotation unit is dependent upon adequate air bubble/solids attachment, which may only be evaluated by laboratory analysis and/or pilot plant studies. The primary variables that govern flotation design are: operating pressures, ratio of pressurized flow to raw waste flow, retention period, and combined particle/air bubble rise rate.

Generally, the detention time will range from 15-30 minutes, the rise rate from 1-3 gpm/ft², and the amount of pressurized flow will range from 15-50% of the raw waste flow. Pressure ranges from 30-70 psig, air requirements range from 0.5 - 1.0 ft³ air/100 gal of pressurized flow, and mixing time for the air and water mixture varies from one to three minutes. Chemicals may either increase or decrease removal, depending on the nature of the particles. Also, hydrophobic solids will float more easily than hydrophilic, adding another dimension to the removal effectiveness of the unit [115, 125].

Future treatment equations should be developed involving all these design parameters. Such development should begin only when sufficient data are available to justify such changes. Laboratory test data are used traditionally to optimize design parameters for effective design. Test procedures introduced by Woods and Dick appear to be a more logical approach to obtaining these values [126].

Rex Chainbelt [115] indicated higher removal rates than allowed by the original model. Although it would appear that modifications are in order, lack of sufficient statistical data precludes such action. Therefore, it is suggested that the existing equations reflecting treatment remain in the revised model.

c) Sedimentation - All equations developed in the original and revised models were based on analyses of domestic sewage and not storm or combined storm wastewaters. The revised equation reflecting treatment effectiveness uses an exponential function based on overflow rate, rather than a linear function based on SS concentration and overflow rate, as used in the original version.

In the report by Heaney and Huber, it was indicated that the revised equation was based on average data rather than instantaneous

measurements [28]. The SS removal is calculated in the model using the function:

$$\text{Fractional SS removal} = 0.82 \times e^{-(\text{overflow}/2780)} \quad (14)$$

BOD removal is based on a fixed 55% of the SS removal.

Further research indicates there are no new developments in this area for either sanitary or storm related wastewaters. Future equations should reflect the nature of the particles in the waste stream (particulate or flocculent) and consider additional settlement due to chemical addition.

7.2.4 Biological treatment

Biological treatment may be defined as the conversion of soluble substrate to microbial biomass and respired elements, with subsequent separation of the biomass to produce a clear treated effluent. With this in mind, it is imperative that clarification be included when selecting this treatment option.

Although this method of treatment is included in the revised model, several limitations are inherent. The most significant limitation is the need to develop and maintain an active microbial population to use the incoming substrate. Without this population, treatment is ineffective. High peak flows cause complications in storm water treatment. Washout of the microbial population is a major potential problem.

A prototype contact stabilization unit in Kenosha, Wisconsin was built adjacent to a dry weather flow plant so that the excess sludge could be utilized by the storm water facility. One report on this operation indicated SS and BOD (dissolved) removals in the order of 92% and 68%, respectively [120]. The report by Lager and Smith includes an excellent review of projects using biological treatment as an approach to storm water pollution abatement.

It appears that biological treatment can be an effective method of reducing pollutional loadings on water bodies when an active biomass is maintained. In the model, SS and BOD removals are set at a straight 80%. When used in conjunction with sedimentation, overall efficiencies should approach 90% for both constituents.

7.2.5 Disinfection

a) Conventional disinfection - The original model included only chlorine contact tanks for disinfection purposes. Chlorine demand was based on 10% of the incoming BOD concentration, but limited chlorine concentrations to the range 6-25 mg/l. The number of chlorinators required was based on the total chlorine demand. Coliform reduction was based on an assumed 99.9% kill efficiency. This appears to be reasonable and has not been altered.

The original model also allowed for a BOD reduction due to chlorination of the waste. Recent research has indicated that the BOD reduction by chlorination of the waste stream was overestimated and that earlier conclusions resulted from a misinterpretation of results and incorrect applications of BOD testing procedures [127]. The report indicated that concentrations of chlorine are not high enough to oxidize the substrate in the wastewater.

In the revised model, all equations accounting for BOD reduction by chlorination have been eliminated.

Other forms of disinfection (e.g. ozone, radiation) are not included in the model. Although ozonation of wastewater is a feasible alternative, the present costs involved are too high. Further advances in research and technology are needed before this option can be included.

b) High rate disinfection - Recent modifications in the original model also include the addition of this treatment process. Modelling of this unit was based on work by Glover and Herbert [116]. This treatment option is similar to contact tank chlorination (including kill rates) with the following exceptions:

- The volume of the tank is selected to provide a two minute detention period at design flow.
- The chlorine demand is taken at not less than 5 ppm and not more than 10 ppm.

Since the work on this disinfection practice is the most up-to-date, no modifications are justified at present.

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